Suppl. Geogr. Fis. Dinam. Quat.
III, T. 3 (1999), 21-48, 29 figg., 3 tabb.

FOURTH INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY - Italy 1997
Plenary Lecture

ANA LUIZA COELHO-NETTO (*)

CATASTROPHIC LANDSCAPE EVOLUTION IN A HUMID REGION (SE BRASIL): INHERITANCES FROM TECTONIC, CLIMATIC AND LAND USE INDUCED CHANGES

INTRODUCTION

Structures, processes and time have been considered a major framework guide of geomorphologic investigations since Davis' classical work (Davis, 1899). The so-called «normal erosion cycle», an imaginary reference of a continuous, uniform and gradually progressive evolutionary pattern evolved from the previous Huttonian ideas and the uniformitarian school of thoughts proposed by Lyell at the end of the XVIII century. The davisian long-duration denudation cycle, following three major time-dependent stages after an abrupt crust-uplift, has been strongly contested. Undoubtedly, the great value of Davis contribution was the projection of landscape over time, being the founder of the evolutionary or historical approach in Geomorphology.

Throughout the XX century, two major schools of geomorphologic thoughts arose: one emphasizing the explanation of landscape morphology and evolution on tectonic basis; and the other, on climatic basis. Despite an extensive literature, fundamental questions remain open. Diverging opinions yet prevail on the role of spatially non-uniform tectonic or neotectonic activities and related questions of local baselevel changes at passive and active margins of the emerged earth surface. Also the deterministic view of landscape morphology as a «mirror» of regional climates has strongly influenced geomorphologic interpretations for some decades. However, recent works have already indicated that similar process-operations may have shaped or still shapes similar morphological features over distinct climatic and geological regions, pointing to the complexity of geomorphic systems.

Both tectonic and climatic schools have influenced unilateral interpretations of landscape evolution. In southeastern Brazil, the analysis of landscape morphology by King (1956) pointed out three major «erosion cycles» associated with the regional tectonic history. The uppermost mountain peaks were related to the post-Gondwana erosion surface and called Sul Americana; the top of the hilly lowlands was inferred as being the remnants of a pre-Cenozoic pedimentary surface, so-called Velhas. Since the Cenozoic orogeny, dissection into this surface has been renewed to form the current pedimentary surface, so-called Paraguaçu. Later in the 60's, however, morphologic and stratigraphic researches led by Bigarella and collaborators in the same region, provided another evolutionary model. They postulated pedimentation processes by following the Quaternary climatic changes to account for the origin of the tropical bevelled surfaces; neither «Davis's Peneplain Theory» nor the «Dynamic Equilibrium Theory» could thoroughly explain their genesis.

According to Bigarella & *alii* (1965) major erosion cycles alternating slope retreat and channel incision would explain the stepped-like SE-brazilian landscape of non-structural benches alternating with steep slopes. The authors suggested that during interglacial/humid climates, the dense vegetation should have favored slope stability and soil development, so that channel incision prevailed (lowering base level stage); transitions to glacial/drier climatic conditions should have rarefied the vegetation cover, so that slope retreat prevailed, leaving behind gently in-

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(*) *GEOHECO/Laboratory of Geo-Hydroecology, Department of Geography, Institute of Geosciences, Federal University of Rio de Janeiro and National Research Council for Scientific and Technological Development, CNPq.*

clined erosion surfaces or pediments. At least two pediment surfaces should have formed during the Pleistocene in association with the glacial periods of Kansan and Illinoian. The greatest planation of these remaining pediplains should be related to Tertiary and Plio-Pleistocene events.

Following Bigarella's work in SE Brazil, Meis and her collaborators have driven special attention to a better understanding of slope retreat and pediment formation, especially during Upper Quaternary times (Meis & *alii*, 1975; Meis & Machado, 1977; Meis & Monteiro, 1978; Meis & alii, 1979; Meis & Moura, 1984; among others). Detailed morphological studies coupled with the stratigraphic analysis of both hillslope and fluvial sediment fills were carried out in the hilly convex-concave lowlands of the middle Doce and Paraiba do Sul river valleys[1]. Meis' works pointed out to a highly discontinuous evolutionary pattern, both on space and time, suggesting at least three major regional episodes of intense erosion rates: in the Middle and Late Pleistocene, and Early Holocene. These episodes alternated with periods of relative morphodynamic stability and soil development, and were associated with changes in the paleo-hydrological regimes.

According to Meis & *alii* (1975) and Meis & Machado (1977) slope retreat was spatially non-uniform, giving origin to the so-called rampas and rampa-complexes[2] (concave up, shell-shaped amphitheaters). To Meis & Monteiro (1978), an individual «rampa» includes an erosive feature in the steeper portion of the upper concave amphitheater and a depositional feature converging to the valley axis at the foot of the slope. The later is filled up with pluri-axial colluvia layers or colluvium/alluvium alternating layers. Rampas have been re-worked and re-shaped over successive periods of time, developing the rampa-complexes. In the headwater zones Meis & Monteiro (op. cit.) described that minor rampa or rampa complexes tend to feed a major one; relative thicker colluvial-alluvial fills may develop wherever a longer valley axis prevail.

At certain places, the headward or lateral retreat of rampa-complexes have led to the destruction of the amphitheater divides or to the coalescence of adjacent rampa complexes. Past relief inversions left behind large amounts of sediments to feed thick alluvial fills at both hillslope and fluvial domains. Coalescense of rampas and aggradation led to the fragmentation of the landscape into isolated convex-shaped hills (called «meia-laranja» or half-orange). Together with stream aggradation, it seems to explain the drowned topography and poorly organized Late Pleistocene drainage network. The re-hierarchization of the regional network has been uncomplete up to the present, so that poorly drained valleys still occur over large areas of the regional landscape.

Meis & Moura (1984) suggested that hillslope processes varied spatially in response to local baselevel changes due to aggradation and degradational processes in the main river valleys: while some rampa complexes were aggrading following a rising baselevel condition, others were degrading together with lowering local baselevel in the main valleys. In her last works at Paraiba do Sul river valley, Meis and collaborators have shown that present-day erosion processes are still highly discontinuous. Oliveira & Meis (1984) pointed out that 65% of gullies occur within the rampa complexes, which represent less than 30% of the hilly convex-concave lowlands. Facing the last results, Meis & *alii* (1985) hypothesized that discontinuous colluvial/alluvial layers should have provided hydraulic discontinuities to explain the dominance of gullying processes along the topographic hollow axis[3]. Some gullies have been developing, as incised channels connected to the headward expansion of the regional network; other gullies developed in separately, in the upper slopes or nearby the slope divides (Coelho Netto & Fernandes, 1990). At certain places gullying has been stabilized, while in other places they are still activated, mirrowing the spatial variability of process-operations.

Late in the 70's I started proccess-oriented field studies, in SE Brazil, being supervised by Prof. M. Regina De Meis during my master degree program (Coelho Netto, 1979); later on, Prof. Jan De Ploey , together with Prof. Meis, supervised my doctor degree program (Coelho Netto, 1985). The main goal was the search for a causal explanation of landscape evolution, to provide a physically based support for Meis's theory of slope retreat and pediment formation. Initial process-studies were carried out at the Tijuca massif in the city of Rio de Janeiro, particularly in the Upper Cachoeira river basin (3.5 km^2) located in the Tijuca National Park (a UNESCO Biosphere Reserve). Our first experimental station was installed in 1975 in order to feed our understanding on process-operations in the present humid Tropical, mountainous landscape.

Early in the 80's we expanded our process-studies to the hilly-lowlands of the Southeastern Brazilian plateau, in the middle Paraíba do Sul river valley, especially in the Bananal river basin (518 km^2). Initially we focused our attention on gullying processes, addressing questions to the explanation of channel initiation and network growth, particularly in the headwater zone where rampas and rampa complexes develop. Then, gullying studies were coupled with the study of valley development, searching for the explanation of process-operations that have shaped and yet

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[1] These two river basins constitute the major drainage systems of the SE Brazilian Plateau.

[2] According to Meis & Machado (1977) the term «colluvial rampa» was initially proposed by Bigarela & Mousinho (1965) to describe slightly inclined valley bottom forms. Later, Meis & *alii* (1975) broadned the use of the term «rampa» to identify gently inclined, slightly concave lower slope and valley flat features.

[3] Later on, Fernandes & *alii* (1986,1994) and Fernandes (1990) verified the relationships between colluvial discontinuities and gullying, as previously hypothesized. The authors have shown that topography still play a major role in controlling the water flow pattern: it converges to the lower end of the valley axis where subsurface flows may exfiltrate. Under critical discharge, excess pore-pressure conducts seepage erosion as a primary mechanism of gully headward retreat, as will be discussed ahead.

shape the rampas or topographic hollows, and regulate slope retreat and relief inversions.

Field investigations have been conducted at distinct hierarchical levels of drainage basins and over different landscape systems, aiming to explore the functional relationships that play important role in controlling hillslope hydrology and erosion processes. More recently, we integrated both functional and historical approaches to improve our understanding on the magnitude of erosion-depositional processes over time, in response to recent environmental changes. Such holistic view of landscape systems, under distinct scales of space and time, was called geo-hydroecological[4] approach.

In this lecture I will summarize the main results and ideas derived from our investigations in the middle Paraiba do Sul river valley and Tijuca massif. Special attention is driven to landscape evolution and the role played by ancient, recent and/or presently geological-geomorphologic and geoecological structures, inherited from tectonic, climatic and land use induced changes.

REGIONAL ENVIRONMENTAL ASPECTS:

The regional landscape shows three major physiographic units: 1) the mountainous ranges, developed in parallel along the coastal zone, including the Coastal massifs, the Serra do Mar and the Serra da Mantiqueira; 2) the hilly convex-concave lowlands with wide, gentle inclined valley bottoms (in the interior plateaus and near the coast) and, 3) the fluvial-marine plains along the coast (so-called baixadas). Figure 1 shows the location of our field-studied areas, around the latitude of 23°S. The Tijuca massif is inserted within the Coastal Range and the middle Paraíba do Sul river valley is bordered by the Serra da Mantiqueira on the left side and by the Serra do Mar on the right ones.

Geotectonic history:

These areas stand on the central portion of the Ribeira Mobile Belt, south of the São Francisco craton, and comprises four tectonic compartments trending NE-SW: one autochthonous and three allochthonous (Lower, Middle and Upper). According to Heilbron (1995) major tectonic events include a compressive/ ductile event associated with the Brazilian Orogeny (Neoproterozoic-Cambric/Ordovician) and responsible by the formation of the mobile belt; the two others, of extensive/ruptile style are related to the Atlantic opening of the passive margin (started in the Jurassic) and to the continental rifting of Neocretaceous and Paleogene ages.

The precambrian tectonic compartments are composed by three lithologic groups (Heilbron, op. cit.): the pre-1.8 G.y basement; the post-1.8 G.y supra-crust and the collisional and post-tectonic Braziliano granitoid rocks. They were generated during the main deformation phase (synauge metamorphic), being limited by inverse shearing zones and associated folding. Later deformations originated another family of open to closed folding and ductile shearing zones. A major regional structure inherited from these ancient times is the mega-synform of Paraiba do Sul (fig. 2-A).

The Cretaceous-Paleogene tectonic is responsible by the rift system of SE Brazil, being characterized by a series of sub-vertical and ruptile faults. Normal faults striking ENE and dipping to SE give the limit to the northern blocks of the Cenozoic sedimentary basins (Resende and Volta Redonda basins-see location in fig. 1). Other faults are mainly transcurrent, striking NW-NNW; the Volta Redonda transtensional zone, striking NW-SE, is a regional feature related to these events. It is a transfer zone connecting the Paraiba and the Guanabara rifts, and has dislocated the Pre-Cambrian mega-synform as suggested by Valeriano & Heilbron (1993). These events have also generated two main regional sub-vertical joint settings, striking NE-SW and NW-SE (fig. 2-B).

Normal faults promoted differential uplifting and subsidence, as much as the exhumation of crust-blocks. Since then, the renewed relief and its underlying litho-structures have been influencing the evolution of the regional drainage systems. The middle course of Paraiba do Sul river runs mostly along the graben of a major normal fault (ENE), changing to NW-SE between Floriano and Barra Mansa where it runs along the Volta Redonda transtensional zone. The Bananal river basin (518 km^2) drains northeasterly the reverse of the Atlantic faulting scarp locally named Serra da Bocaina (fig. 2-C); the Turvo river drains southeasternly to the Volta Redonda transtensional zone-see details bellow figure 2.

Recent environmental changes:

The Quaternary Era was characterized by global climatic changes, alternating major glacial periods with relative warmer-interglacial periods during the Pleistocene; glacial sheets did not reach southeastern Brasil. The Pleistocene-Holocene transition (around 10,000 years BP) was marked by changes in the global air circulation, providing relative warmer and wetter conditions (Ledru,1993); the same tendency was shown by Absy & *alii* (1991) and by Van der Hammen & Absy (1994) in northern Brazil. Taking into account the present air circulation over SE Brazil, one might expect an increasing frequency of intense rains in response to global or local warming. This is related to the stronger thermal impact of Polar air masses over the Tropical Atlantic air mass (relatively warmer and wetter) that dominate the region all over the year.

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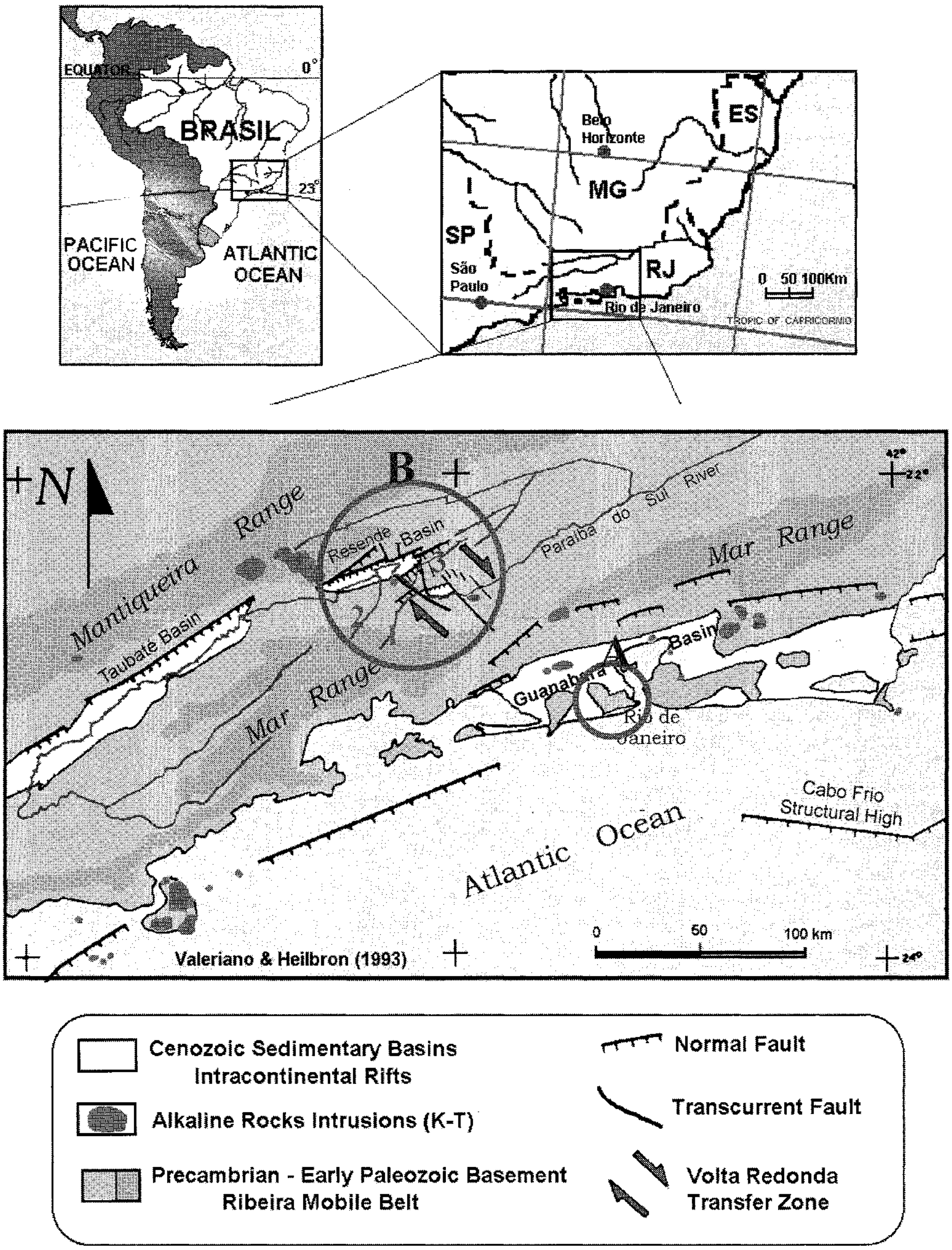
[4] The term geo-hydroecology was created by the present author to express an integrative-analytical approach for the study of landscape systems (or geoecosystems). The term landscape is here appropriated under both geoecological and geomorphologic perspectives. In the first case, as a set of interacting ecosystems at distinctive hierarchical levels; in the second one, as a surface composed of an assemblage of transient or steady state landforms. Water is viewed as a linking-element of the terrestrial spheres (atmosphere, lithosphere, biosphere, homosphere), exerting an important role in controlling interdependent or functional relationships that govern process-operations within a given geoecosystem.

FIG. 1 - Location map of southeastern Brazil and field-study areas at Tijuca massif (small circle) and middle Paraíba do Sul river valley (big circle).



Paleoenvironmental studies conducted in Brasil have indicated vegetation changes in response to the Holocene climatic transition. In central Brasil, Ledru (op. cit.) found evidences of mountain forests (with 78 to 91% of tree species) under cool/wet climate from 34,000 to 17,000 years BP; from 17,000 to 14,000 years B.P the tree species declined to 24% due to changes toward to relative drier and coller climate (−6 °C); the proportion of tree species increased from 13,000 to 10,500 years B.P (still cool, but humid); a longer drier period lasting from 10,500 to 10,000 years B.P led to small decrease of trees; then, from 9,000 to 5,500 years B.P tree species increased again, attaining 30 to 72% due to warmer and wetter climatic conditions.

The literature points to minor climatic changes toward relative drier conditions in the mid-Holocene (from 5,000 to 2,000 years BP); probably the forest vegetation rarefied during this period. For the last couple of thousand years however, the original Tropical Atlantic rainforest has fully developed, until land exploitation started due to the european colonization. In the mid-XVIII century, the original Atlantic rainforest was devastated, being substituted by extensive coffee plantations throughout SE Brazil (until late

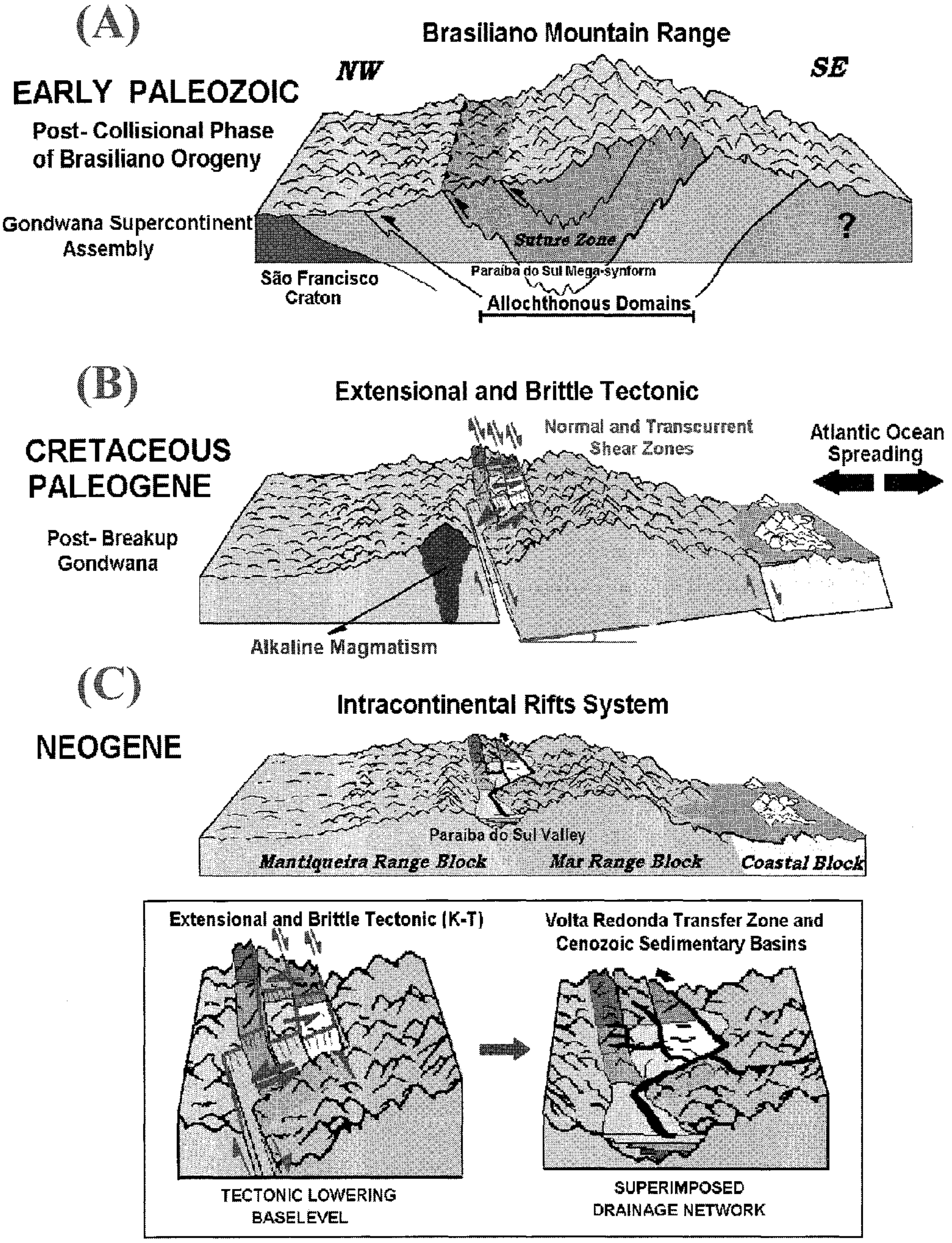


FIG. 2 - Sketched diagrams of the geotectonic context of SE Brazil: A) Gondwana supercontinent assembly; B) Post-break up of Gondwana; C) Post-Cenozoic rifting; bellow: detailed view at Volta Redonda transfer zone and superimposed drainage network (main channel is the Paraíba do Sul river; the Bananal river is on the right valley side and the Turvo river is on the left valley side.

XIX century)[5]. Such regional deforestation led to a dry-spell period in the winter, as described in historical documents (Dantas & Coelho Netto,1995). After the economic decline of coffee plantations, grasslands and cattle grazing spread all over the middle Paraíba do Sul river valley. Nowadays grasslands remain among sparse patches of late-secondary rainforest. Presently the region is under Humid Tropical climates, including: Köppen's Cf type, in the upper mountainous ranges and Köppen's Am/Aw in their mid-lower portions and hilly lowlands.

Since the mid-twenty century, industrialization and urbanization increased significantly at different localities. According to Brandão (1992), industrialization and urban growth at big cities led to an increasing air temperature

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[5] Coffee plantations also spread onto the steep slopes of the Tijuca massif in the city of Rio de Janeiro, up to the mid- XVIII century. However, the increasing need for water due to population growth led the governmental authorities to expropriate the local coffee farms. Then, an official reforestation program was installed in 1860: around 90,000 heterogeneous native species were introduced, specially in the headwater zones. So the local Atlantic rainforest is nearly 140 years old and has reached an advanced succession stage.

and rainfall concentration in the summer, as exemplified by the city of Rio de Janeiro. Despite the strong urban pressure in the surrounding areas of Tijuca massif, a late-secondary rainforest remains partially preserved in the mid-upper portion (inserted in the Tijuca National Park). However, deforestation is advancing rapidly onto steep slopes at rates around 0.8 km^2/year (for the period 1966-1990), in response to both formal and informal human settlement, fire and air pollution. (Fernandes & *alii*, 1998).

For SE Brazil, Meis & *alii* (1981) found that annual precipitation has been decreasing throughout this century and variations on the frequency of moderate-intense rains regulate the annual totals. Presently, mean annual precipitation ranges from 1,300mm in the hilly lowlands to above 3,000mm in the upper mountainous lands; the seasonal rainfall regime is marked by a drier period from May to September, with increasing monthly precipitation towards summer. Intense rains are mostly associated with warmer periods (from January to April) caused by the stronger thermal impact of cold fronts provided by Polar air masses against the dominant Tropical Atlantic air mass (Coelho Netto, 1979, 1985).

In the upper portion of Tijuca massif at Rio city, the author shows an average monthly rainfall around 130 mm. In the high-summer of regular years, mean monthly rainfall is on the order of 250 mm. Extreme monthly totals may attain above 900 mm, particularly due to an increasing frequency of intense rains (>100 mm/day). Extreme rainfall events tend to occur in the hottest month (February). In February 13, 1996, the very extreme rainfall intensity was recorded at Tijuca massif, reaching 380 mm in less than 24 hours. This event followed a long period of anomalous temperatures (above 40 °C) due to El Niño effects.

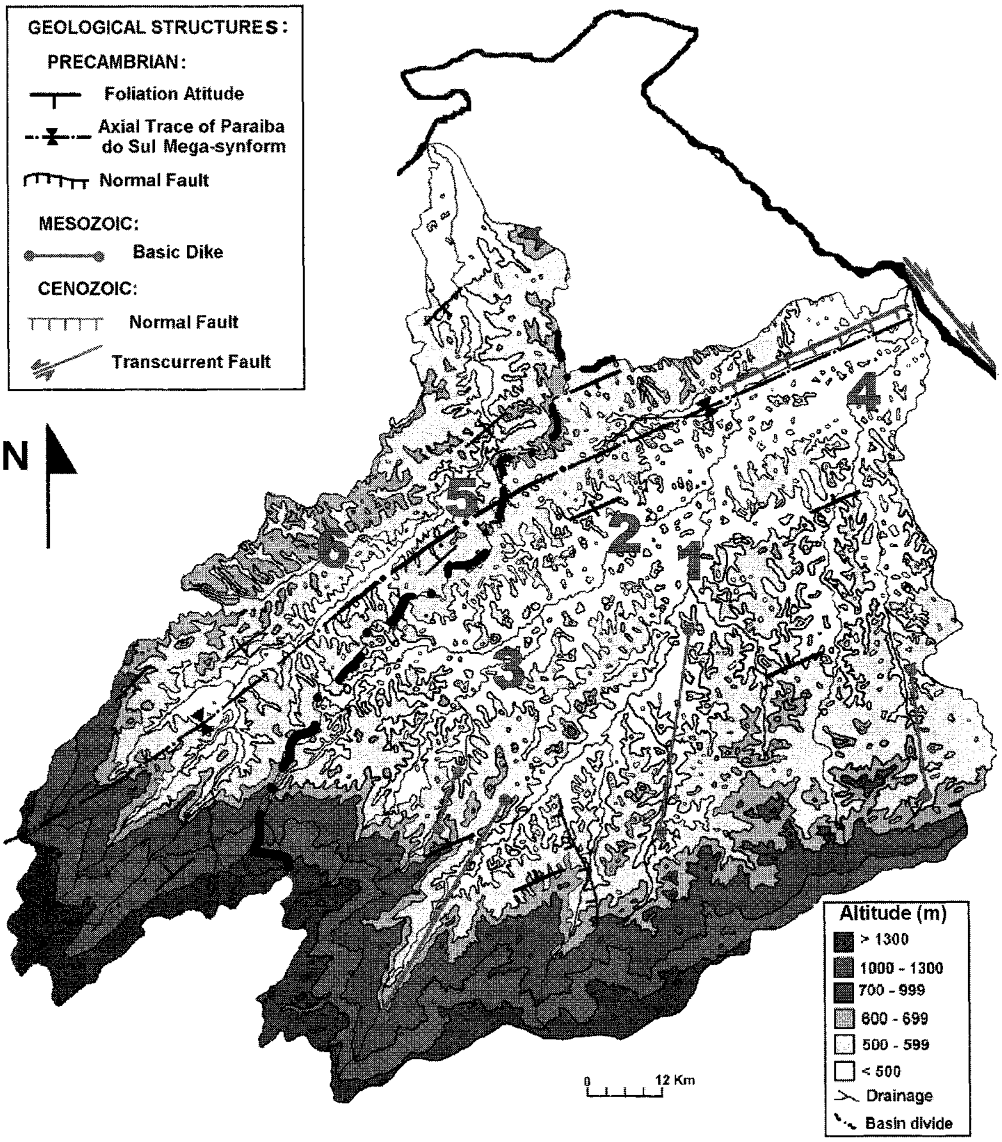


FIG. 3 - Hypsometric map of the Bananal and Barreira de Baixo river basins: 1) Bananal river; 2) Piracema river; 3) Manso creek; 4) Carioca river; 5) Barreiro de Baixo river and 6) Campo Alegre creek.

THE BANANAL RIVER BASIN

The Bananal river basin drains two major physiographic zones: 1- the mountainous zone, above 600 m height, with steep slopes and narrow valley bottoms, and 2- the hilly lowlands, where large and gentle inclined valley bottoms prevail bellow the 500 m contour lines (fig. 3). This hypsometric map shows an extensive surface (in light grey) between 500 m and 600 m height, which constitute the main interfluves of the Bananal basin, including the divide between the Bananal basin and the Barreiro de Baixo basin, another tributary of Paraíba do Sul river. This surface has been strongly dissected in the mid-lower Bananal basin, especially along the mid-upper Piracema creek, the main tributary channel of Bananal river running SW-NE. The average hilltop elevation profiles decrease toward the Paraíba river at both tributary basins, being previously interpreted as the remnants of an older pedimentary surface (King, 1956; Bigarella & *alii*, 1965).

In its lower course, the Bananal river runs parallel to the pre-Cambrian mega-synform, cutting off an ENE normal faulting of Cenozoic age, as shown in the same figure 3. Upstream, it follows the NW-NNW faulting related structures of the same age. In its middle-upper course, it follows the strike of the Pre-Cambrian bedding, dissecting into weaker-resistant bedrock layers. The main tributary channels have been also dissecting along the strike of the underlying bedding (ex.: Piracema river) or in parallel to the NW-NNW faults (ex.: Carioca river), while many others minor tributary valleys have been controlled by sub-vertical joint settings striking SW-NE and SE-NW.

Figure 4 shows the main topographic compartments for second order basins (according to Meis & *alii*, 1982). Yet can be seen the location of bedrock knickpoints along the river channels, varying from small rapids of 1.5 to 5.0 m, up to steep and high waterfalls of 30 to 50 m height, at both mountainous and lowlands compartments. These features control the development of a stepped-landscape with

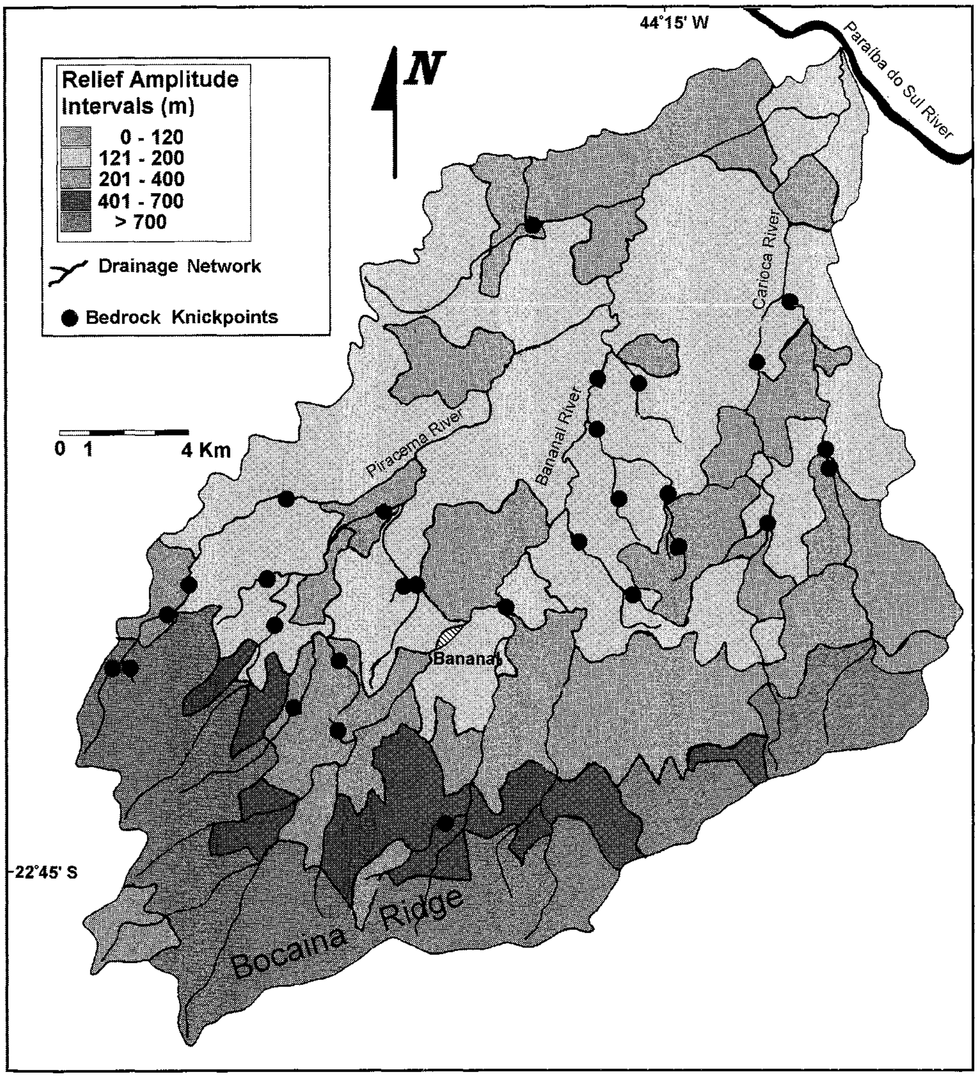


FIG. 4 - Bananal river basin: topographic compartments for 2nd order tributary valleys (according to Meis & *alii*, 1982).

successive hanging valleys operating independently of the regional system. Silva & *alii* (1994) have shown that 80% of these knickpoints are associated with sub-vertical joints; most of which striking SE-NW, orthogonal to the main bedrock foliation. Dantas & *alii* (1994) observed that valley width gets narrower at knickpoint places; larger sedimentary alveolus occur upstream the knickpoints.

The Bananal basin has been dissecting into the upper tectonic compartment of the Ribeira Mobile Belt. The geological background is composed by high grade metamorphic rocks of Pre-Cambrian age, including the pre-1.8 G.y basement (orthogneisses), the meta-sedimentary sequence of the Páraiba do Sul Group and the granitoid rocks, all striking NE-SW and dipping 20° to 40° NW, as shown by Silva & *alii*, 1994; Almeida & *alii*, 1993;1991 (fig. 5). The late authors have subdivided the Paraiba do Sul Group in three main lithological units, including the following sequence from the base to the top: 1) Três Barras unit:banded biotite gneiss, with lens of calc-silicates rocks and pelitic schist; 2) São João unit: sil.-garn.-musc.-biot.-gneiss, with gondite levels, calc-silicate rocks, pelitic schists and marble; 3) Beleza unit: banded biotite gneiss, with several intercalations of calc-silicates rocks, pelitic schists, gondite, marble and quartzite. The granitoid rocks were sub-

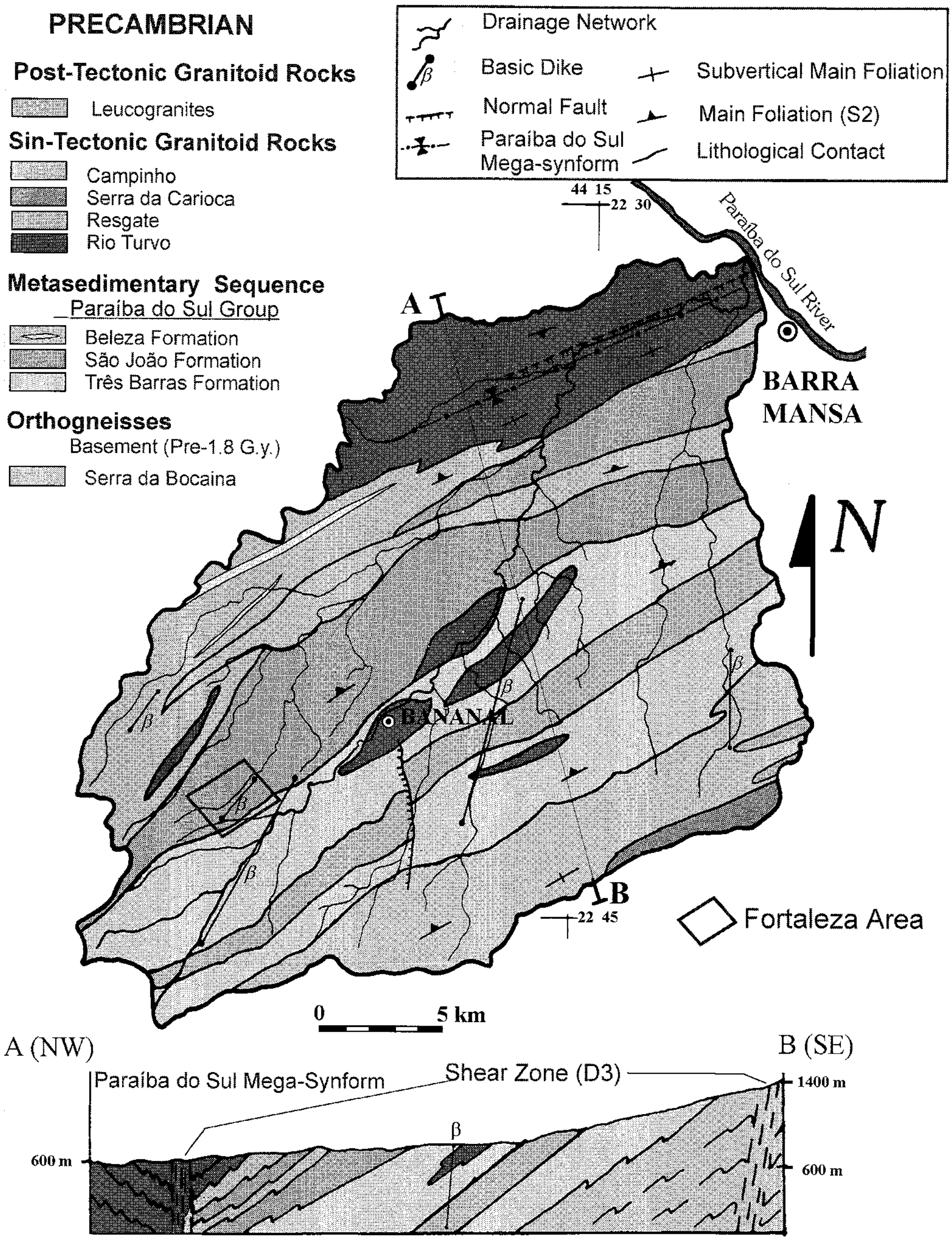


FIG. 5 - Geologic map of the Bananal river basin and geological transect A-B (Silva & *alii*, 1994); location of the Fortaleza area.

divided into five main units, as follows: 1) Rio Turvo: porphyritic granite/biotite gneiss; 2) Serra da Bocaina: hornbl.-biotite gneiss; 3) Resgate: turm.-biot.-musc.-schist quartz gneiss; 4) Campinho: biot.-hornbl. gneiss; 5) Taquaral: granodioritic biot.-hornbl. gneiss and leucocratic granite.

Thick weathering profiles are found in the hilly lowlands (above 20 m thick); they tend to become shallower toward the steeper slopes of the mountainous zone. Bare rock escarpments occur on the steepest slopes (above 50°). Rock bedding, together with dikes and joint settings led to differential weathering processes: in the hilly lowlands, a highly heterogeneous saprolite developed and significant hydraulic and mechanical discontinuities interfered and yet interfere on process-operations in the hillslope domain, as will be discussed further on.

Structurally controlled landforms in the headwater zones

The amphitheater-like morphology of rampas and rampa complexes, or concave up topographic hollows, may vary within the headwater zone of the Bananal drainage system. Two major shapes prevail: one is broad and shallow with smooth borders (fig. 6); the other is relatively deeper, larger in the upper portion and narrowing abruptly at the lower end (fig. 7). Both shapes may develop at grade to the adjacent valley bottom or at hanging; the late case will tend to degrade until reach a grade condition to the adjacent valley bottom. Such topographic adjustment is associated with channel incision; discontinuous or continuous channels may develop onto the steep slopes bellow the hanging valley bottom, before reaching the adjacent stream channel. The «narrow-end» shaped hollows are found in the mountainous and hilly lowlands compartments.

An example of «narrow-end» mountainous-hollows, is pictured in figure 7 cited above. These four hollow axis have developed in parallel to each other, being hanging in relation to the adjacent Fortaleza creek valley bottom. Detailed geologic-geomorphologic map (1:10 000) carried out in this area by Almeida et al. (not yet published; see location in figure 5) provided the following observations (fig. 8): a) hollows are dissecting into the São João unit, being limited in the uppermost slope divide by the Três Barras unit; b) the underlying rock bedding dips around 40° NW; c) in this locality, the São João unit alternates pelitic gneiss and schist bands with distinct mineral and textural composition; d) the rocky band composed by tourmaline, silimanite, garnet, biotite, porphiroblastic gneiss, rich in leucossomatic levels and lenses of calcium-silicate rocks, pelitic schists and marble, is concordant with the height of their respective lower ends or hollow outlets, as illustrated in figure 8-B. Down the hollow-outlets, small channels are dissecting along sub-vertical joints striking NW-SE, orthogonal to the underlying rock bedding.

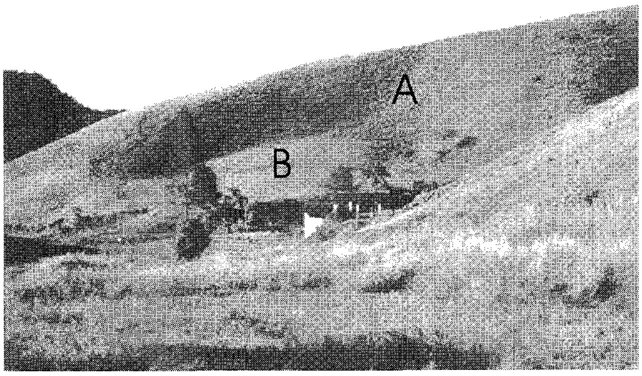


FIG. 6 - Broad-shallow topographic hollow, grading to the valley bottom at Fortaleza creek sub-basin, Bananal basin.: A) erosive feature originated by landslides of slump type; B) depositional feature.

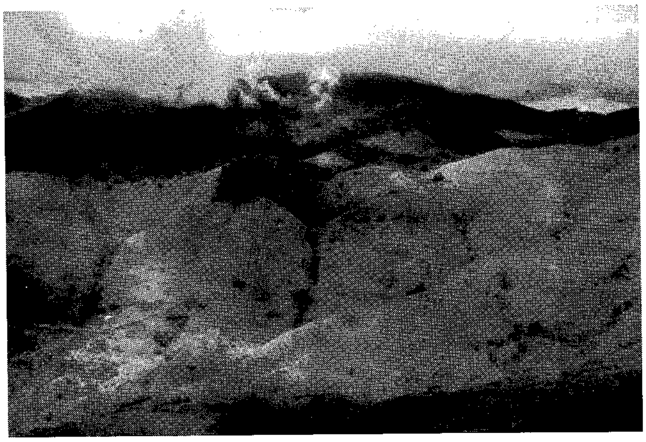


FIG. 7 - Adjacent narrow-end topographic hanging hollows at Fortaleza creek, draining the mountainous compartment of the Bananal river basin.

In the headwater zones of the hilly lowlands of the Bananal basin, Avelar & Coelho Netto (1992 a) have shown that joint density varies according to lithological units, being higher in the Três Barras unit (1.82/m^2); intermediate in the São João unit (0.78/m^2) and lower in the Rio Turvo granitoid rocks (0.14/m^2). However, the average orientation of joints and valley axis are very close in all lithological units, at distinct hierarchical levels of the drainage system, excluding the valley axis of «broad-shallow» topographic hollows. «Narrow-end» hollows predominate over «broad-shallow» hollow types in all lithological units: in the highly jointed Três Barras they represent 75.6% (n=86), while in the less jointed Rio Turvo they attain 70.7% (n=58).

Most of «narrow-end» hollows develop at grade to the adjacent valley bottom: only around 20% occur hanging in the Três Barras mapped area (15 km^2), increasing to 31% over the Rio Turvo granitoids (within an area of 15 km^2). Visiting several «narrow-end» hanging hollows (n=51), we confirmed the parallelism between their respective hollow axis and the strike of local joints. Joints were seen along the channel system, bellow the hanging valley axis, and also in the side wall of tunnels which are progressing backward at the channel heads.

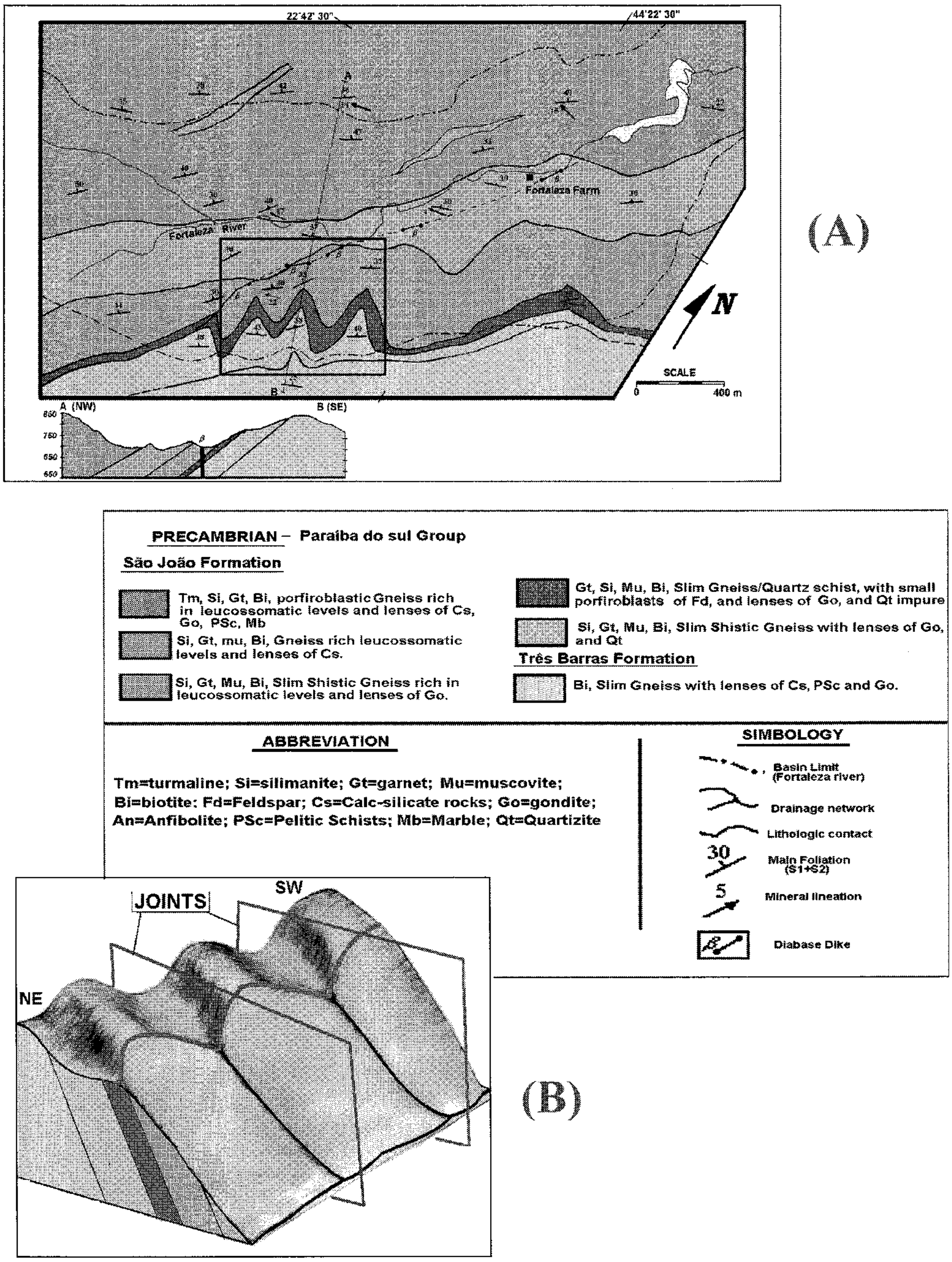
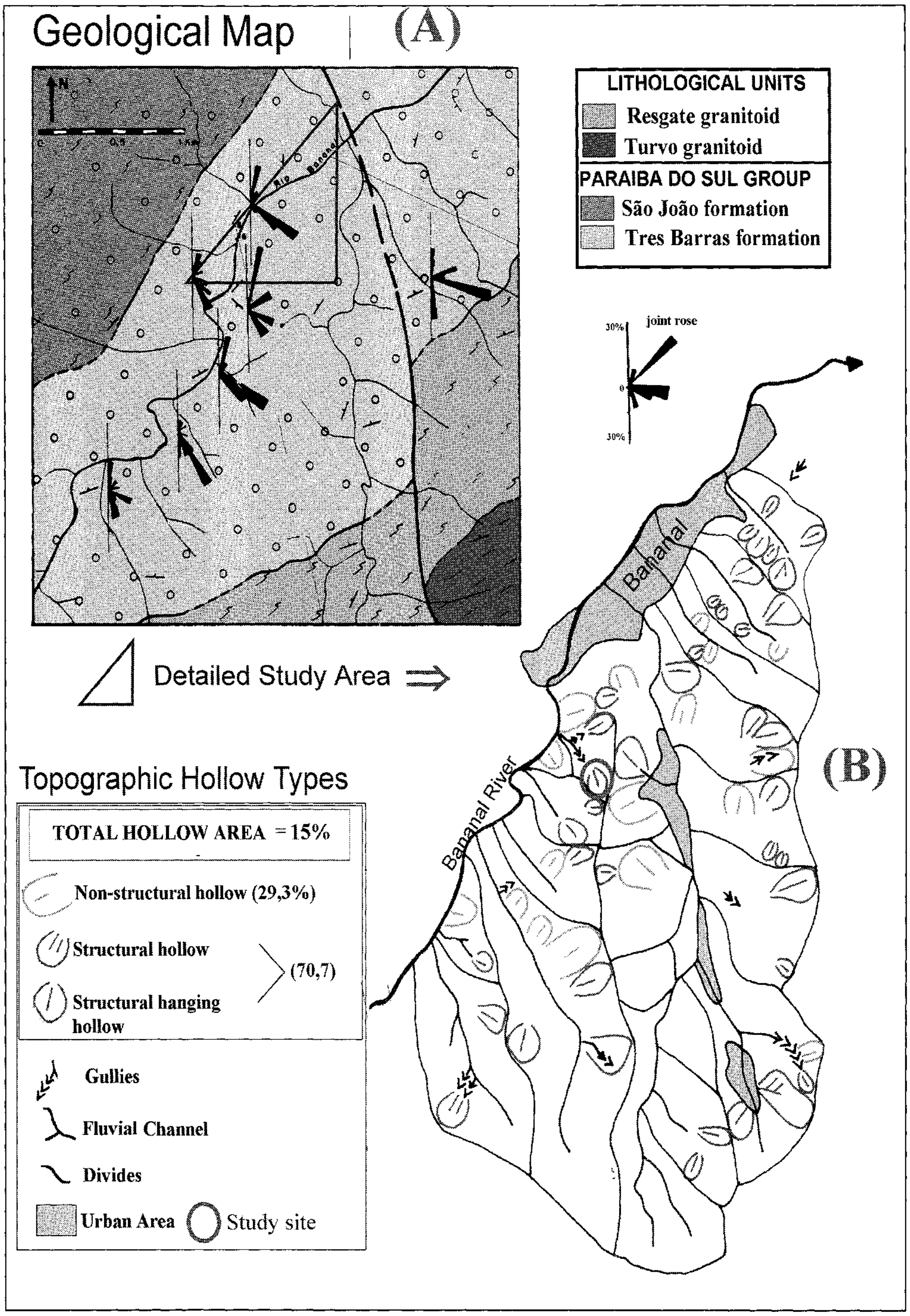


FIG. 8 - (A) Detailed geological map of the Fortaleza area; (B) Sketch diagram of the «narrow-end» hollows and underlying litho-structures.

Aiming to provide a better understanding on the origin of «narrow-end» hollow shapes and their relationships with sub-vertical joints, a piezometer network was installed in a typical hanging hollow developed on granitoid rocks at Bom Jardim area. As this lithological unit is relatively homogeneous, joints should be considered as a major hydrological discontinuity within the soil mantle. Figure 9 shows the location of the studied area and figure 10 points the piezometer network along the major and minor hollow axis, reaching two colluvial layers and the saprolite at different soil depths.

Avelar & Coelho Netto (1992 b) observed that water occurred temporally, only within the saprolite and along the hollow axis, as shown in the same figure. Hydraulic head decreased downward, toward the lower end of the hollow axis, so that the piezometric surface occasionally intercepted the topographic surface right bellow the hanging hollow axis. Thus exfiltration of groundwater flows at the channel head of a discontinuous channel system, involved seepage erosion and tunneling within a local sub-vertical joint, which strikes parallel to the orientation of the above hollow axis. Hydraulic conductivity within the saprolite

FIG. 9 - (A) Detailed geological map (1:10 000) at Bom Jardim area; (B) spatial distribution of distinct topographic hollow types; location of the studied hanging hollow.



is on the order of 10^{-5} cm/sec., decreasing linearly with depth. Lower permeability values were found in the nearly fresh rocks along the discontinuous channel system, where tunneling is activated. Rates of tunnel erosion is on the order of 0.1 m^3/y according to field measurements from 1990 to 1992.

Facing the results above, Avelar & Coelho Netto (1992 a) stated for the Bananal basin that bedrock hollows may primarily develop under structural controls or not. Structurally controlled bedrock hollows predominate, being associated with artesian or ascending groundwater flows throughout sub-vertical joints (as seen in the Bom Jardim area) and wherever joints intercept less permeable rock bands or stand upward subvertical dikes (as in the Fortaleza cases, described earlier). Seepage erosion and tunneling are responsible for channel initiation, after col-

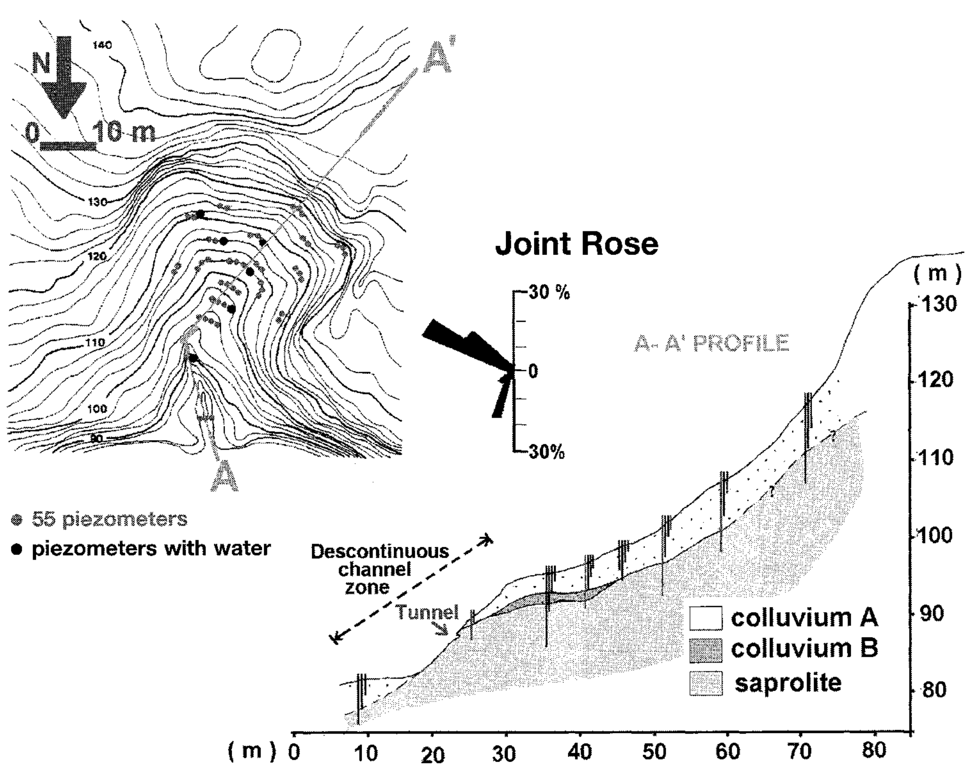


FIG. 10 - Detailed topographic map of a hanging topographic hollow at Bom Jardim area and location of the piezometer network; local joint rose and cross-profile with main subsurface structures with related piezometer depths (see location of the measured tunnel progressing along a joint at a minor channel head).

lapsing the tunnel roof; the linear and headward progression of channel incision would tend to trigger landslides above the channel head. So landslides and subsequent erosion onto the erosive scars should be responsible by the origin of the amphitheater-like morphology with narrow lower-end (fig. 11-above).

Hillslope sediments converging from the upper portion of bedrock hollows[6] remained partially stored in its lower portion, while another part was left over the hollow-mouth, feeding a major hollow axis; minor colluvial cones were formed bellow the hanging bedrock hollows. In figure 11-below we sketched our imaginary view of the Pleistocene landscape, including an individual bedrock hollow at hanging, in relation to the regional channel network. We also sketched the present landscape, emphasizing the interactions between hillslope and fluvial processes: the previous bedrock hanging hollow is already at grade to the adjacent valley bottom, and distinct colluvial layers intercalate or overlay thick alluvial-colluvial fans and fluvial deposits, respectively in the lower-order tributary valley bottoms and/or along the main one. Thick sediment fills drowned the previous drainage system, so the channel network has been renewed in the Holocene: a fill terrace was formed and then, the current insert floodplains developed.

Geomorphic responses to recent environmental changes

To reconstruct the recent erosion-depositional history of the studied drainage basin, a thorough stratigraphic survey was conducted in cooperation with William E. Dietrich, from University of California at Berkeley (Dietrich & *alii*, 1991; Coelho Netto& *alii*, 1994). The main goal was to provide a better understanding on the causes of aggradation and degradational cycles at a basin and local scales. A consistent collection of charcoal samples provided absolute dating[7] for both hillslope and fluvial sediment fills.

Figure 12 shows the stratigraphic profiles and respective dating along the Bananal river and main tributary valleys: from the lower basin to the mid-upper one, a synchronous aggradation cycle started around 10,000 years BP, being interrupted abruptly around 8,000 years BP. At only one place we found a young layer of 4,540 years BP probably related to local conditions. No Pleistocene deposits were found along the main channel system, suggesting that rivers were previously running over bedrock. Pleistocene lag-deposits were preserved only at the base of some alluvial fans, in the hillslope-fluvial interface. Strati-

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[6] It would correspond to the first generation of a certain type of rampas (structurally controlled rampas).

[7] One hundred sediment samples were taken at 24 sites, being 10 in the fluvial domain, 10 on hillslopes and 4 in the transitional infilled valleys (alluvial fans) where hillslope sediments may interfinger or overlay the fluvial deposits. ^{14}C AMS dating was conducted in the Lawrence Livermore National Laboratory at California.

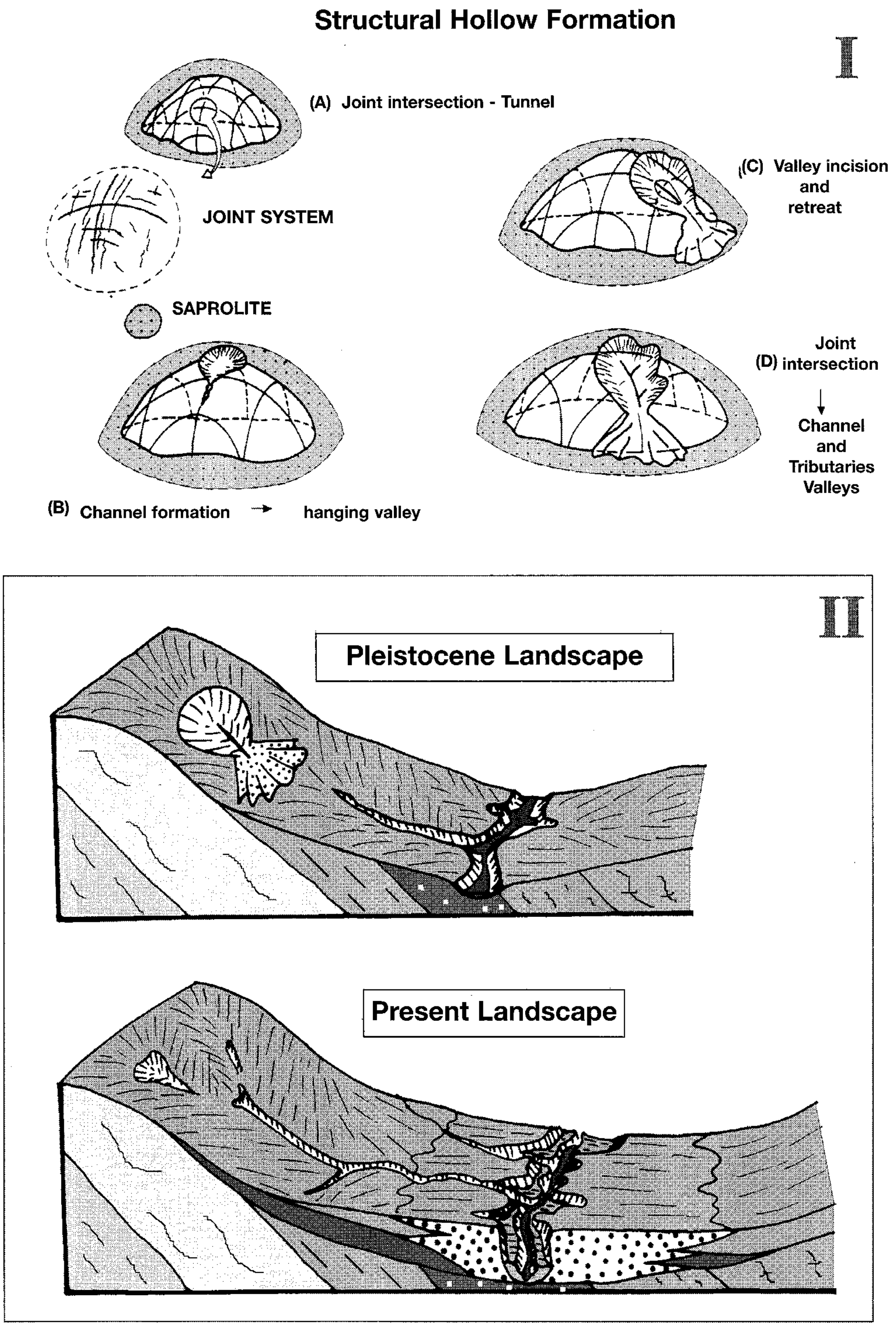

FIG. 11 - (I) Sketched diagrams showing the origin of structurally controlled topographic hollows: 1) joint intersection favor exfiltration of artesian ground water flows providing the development of tunneling by seepage erosion; as tunneling progresses backward, the roof will tend to collapse giving origin to an open channel; 2) the headward progression of channels may trigger landslides to open the amphitheater-like morphology above the channel head; such process-chain may reproduces in hanging (as shown) or grading the adjacent valley bottom; 3) valley incision and slope retreat tend to progress episodically; 4) the growth of tributary channels and valleys may be favored by joint intersection; (II) Sketched diagrams showing: an imaginary view of the Pleistocene landscape and reproducing the present landscape and major depositional structures.

graphic inversions were observed in alluvial fans and fill terraces, being provided by sediment transfer from the uppermost headwater zones where Pleistocene lag-deposits are still preserved, as will be shown ahead. The floodplain deposits were largely stored from 200 years BP up to around 100 years BP.

The stratigraphic interface of hillslope and fluvial sedimentation can be exemplified at Bela Vista amphitheater, an infilled 1st order-valley connected to Piracema river, the main tributary of Bananal river (fig. 13). The location of the main diagram is shown in the small topographic map: it corresponds to the valley bottom of a typical «-

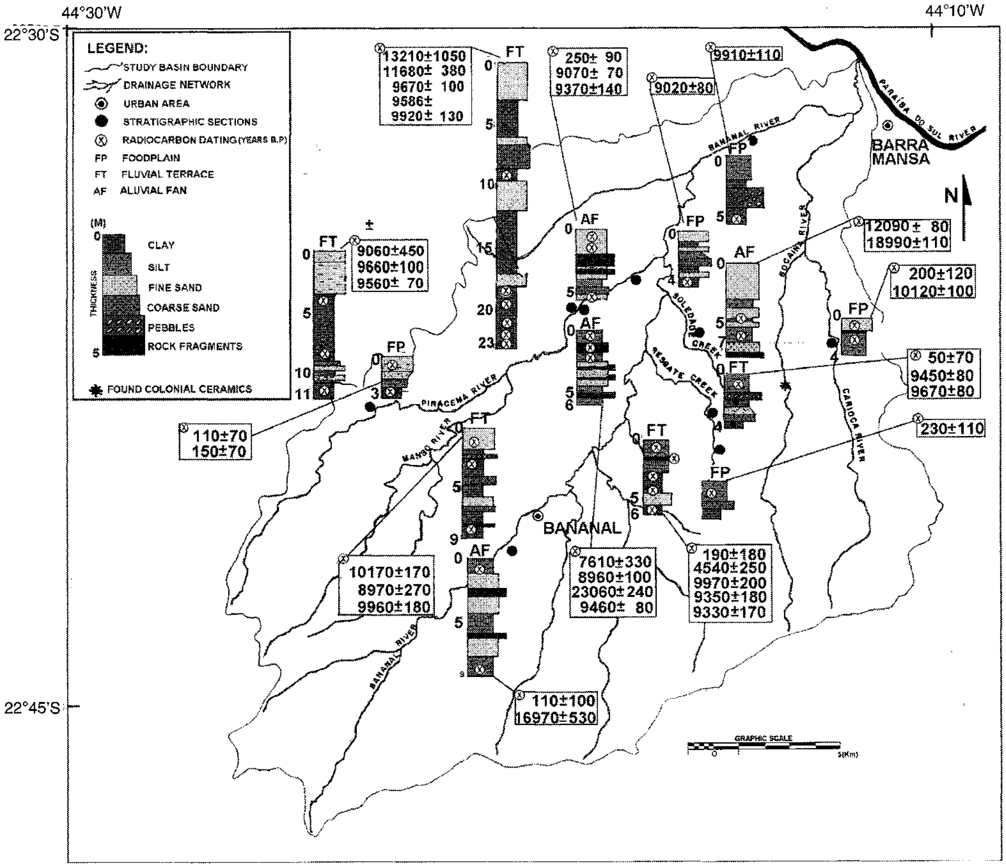

FIG. 12 - Stratigraphic profiles and C^{14} AMS dating of the alluvial fans (AF), fill terrace (FT) and insert floodplain (FP) along the main valleys of the Bananal river basin.

narrow-end» hollow shape at grading to the adjacent Piracema valley bottom. Fluvial sands and organic clays are seen at the bottom of the lower stratigraphic profiles (P7 and P4, respectively) above which a thick, loose and highly permeable alluvium-colluvial fill developed with planar structures and alternating layers of variable texture. Distinct colluvial layers, converging from the upper topographic hollows, intercalate and overlies these loose mate-

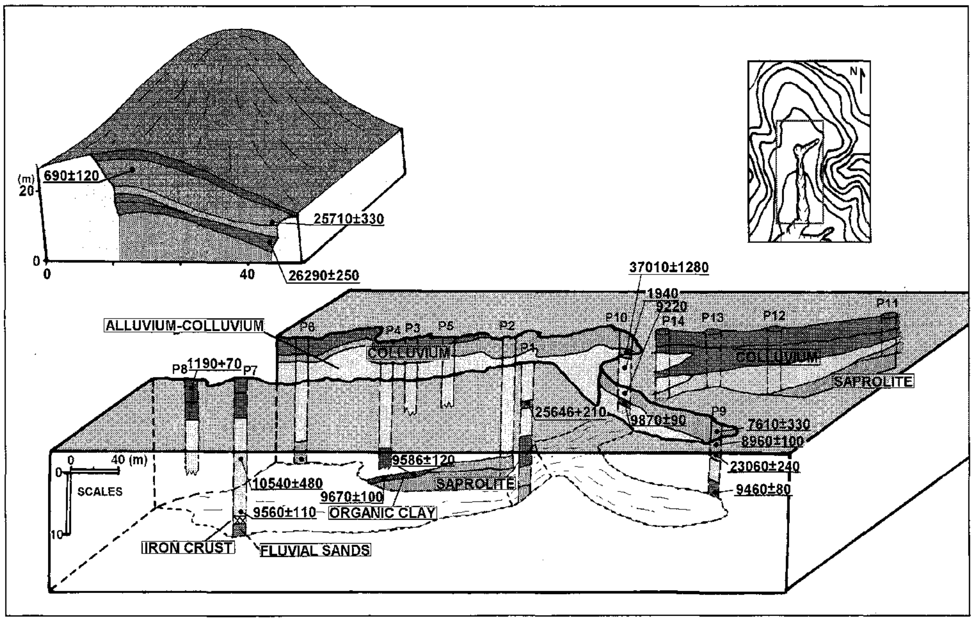

FIG. 13 - Stratigraphic profiles and C^{14} AMS dating of the alluvial-colluvial fan at Bela Vista amphitheater, dissected by a first-order tributary gully of Piracema river. Above/left- stratigraphy and C^{14} MAS on sideslope; Above/right- location map of the main figure.

rials. The whole system is a typical «rampa complex», where minor «rampa complexes» feed the major one.

Dating shown in Figure 13 clearly indicates that hillslope sedimentation buried the adjacent fluvial domain during the aggradation cycle around 10,000 to 8,000 years BP. At P9 one may observe a stratigraphic sequence alternating colluvium and alluvium deposits, and also an stratigraphic inversion. As mentioned before, this inversion is related to the re-working of older Pleistocene colluvium still preserved in the upper, minor tributary rampa-complexes, as illustrated in figure 11-Above/left . In two other profiles (P8 and P10) we found younger layers of ages about 1,190 and 1,940 years BP, respectively, but of local representation.

In the lower portion of the Bela Vista amphitheater one may observe in detail the stratigraphy of a minor colluvial cone converging to the main valley (fig. 14). It developed right bellow the mouth of a «narrow-end» hollow, previously hanging; coarse-debris colluvial layers alternate with gravel-sandy and finer ones, showing inclined and planar strutures. Deposition also buried the fluvial sedimentation, intercalating and overlying the alluvial fan converging from the 1st order trunk-valley. Such overlapping of colluvia-alluvial layers, articulating from the minor to the major topographic hollow axis and then, to the adjacent river-valley bottoms, corresponds to the stratigraphic pattern previously described in Meis's works as related to «rising baselevel conditions». More recently, the drowned valley floors were covered by a thin layer of about 200 years BP, also illustrated in figure 14.

Another minor rampa-complex was investigated on stratigraphic basis at São João area. It converges to a 1st order tributary channel of the Bananal river, as indicated in figure 15. Fernandes & *alii* (1986) and Fernandes (1990) identified distinct colluvial layers, applying the same allo-stratigraphic criteria used in Moura & Meis (1986); later on we dated some of them. Evidences of paleo-channels are shown in the 3-D diagram: the oldest generation (phase I) was dissecting into the saprolite before being buried by Pleistocene colluvial layers (17,980 ± 1720 BP) over which a soil profile developed; another paleo-channel (phase II) cut off the paleo-A horizon (10,030 ± 60 BP), leading to the lateral mobilization of the previous hollow axis. Both paleo-channel II and paleo-A horizon were buried by colluvial layers related to the erosional-depositional cycle from 10,000 to 8,000 years BP. At São João site we also found a colluvial layer of about 1,000 years BP, which was recovered by the youngest layer of about 200 years B.P . The present channel tip, has developed in connection to the regional channel network, following the same route of paleo-channel II in the lower hollow axis. The older sequence of truncated colluvial layers shown at São João, corresponds to the stratigraphic pattern previously described in Meis's works as related to «lowering baselevel conditions».

In figure 16 we plotted all dating collection obtained for fluvial deposits, alluvial fans (fluvial-hillslope interface) and colluvia sequences. Pleistocene lag-deposits of variable ages (from 38,000 to 17,000 years BP), found only in the hillslope domain, does not show any clear aggradation cy-

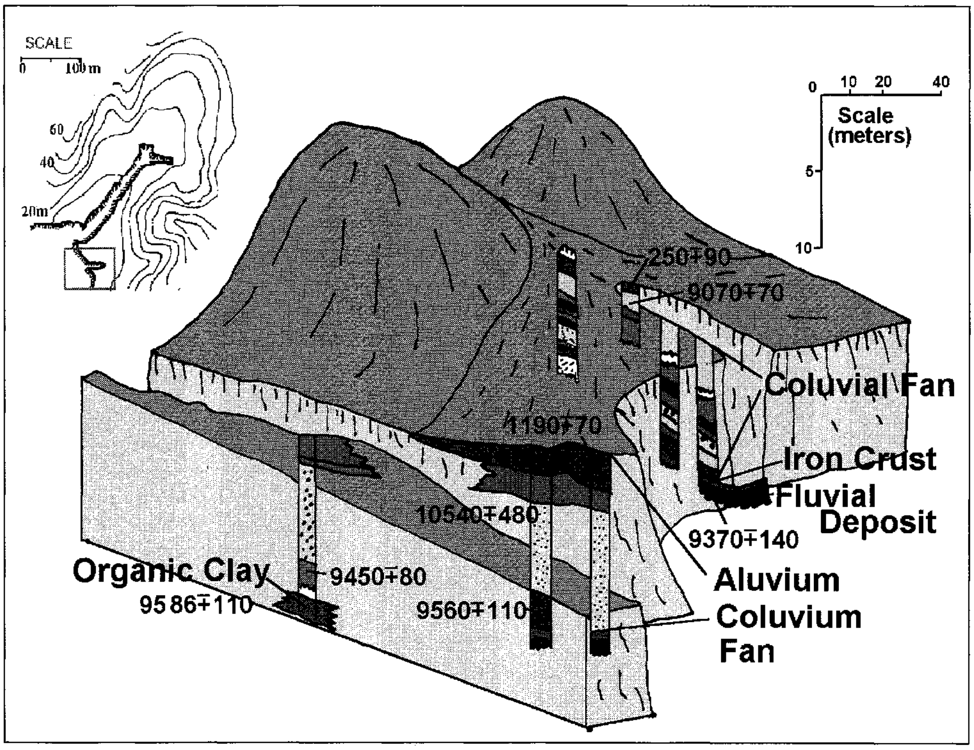

FIG. 14 - Stratigraphic profiles and C^{14} AMS dating of the colluvial fan at the base of a minor topographic hanging hollow in the lower portion of the Bela Vista amphitheater; a gully tip is advancing through the fan. Above/left-location map of the main figure.

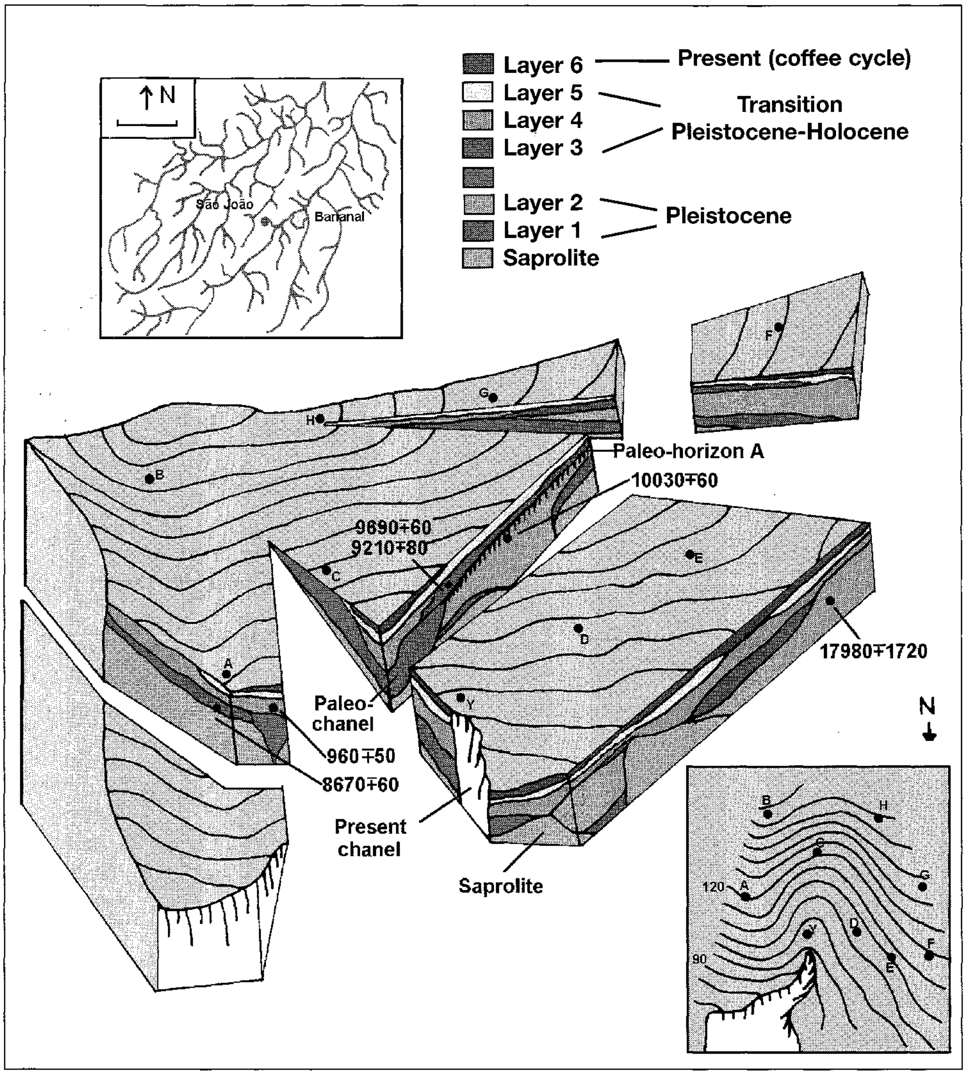

FIG. 15 - Hillslope stratigraphy and C^{14} AMS dating of the colluvial layers at São João area; above/left) location of the site; below/right) location of basic stratigraphic profiles (modified from Fernandes, 1990 and Coelho Netto & Fernandes 1990).

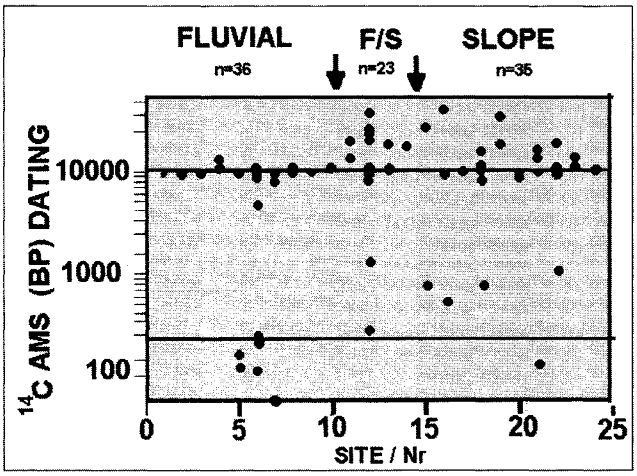

FIG. 16 - Collection of C^{14} AMS dating of representative sediment samples from the fluvial, hillslope and transitional (F/S) domains of the Bananal river basin.

cle. The paleo-A horizon of about 10,000 to 9,500 years BP was found in several hillslope sampled sites, confirming its regional extension as previously indicated by Moura & Meis (1986) and Moura (1991). Following this period of relative morphodynamic stability and soil development, the synchronous erosion-depositional cycle spread all over the Bananal drainage basin around 10,000 to 8,000 years BP. Then a new period of relative morphodynamic stability and soil development extended over most of the Holocene. Sparse colluvial layers of age varying from 2,000 to 500 years BP were not consistent enough to characterize another generalized erosion-depositional cycle. The new one occurred only about 200-100 years ago as indicated by charcoal samples at both fluvial and hillslope sediment fills, and also by the presence of european ceramics from colonial times.

The 10,000-8,000 years BP erosional-depositional cycle was probably a response to global Pleistocene-Holocene climatic transitions. As it happens nowadays in SE Brazil, warming up air temperatures may have provided an increasing frequency of intense rains over weaker-resistant soil mantle. At that time soil properties should have been associated with the previous climatic conditions, cooler and drier from 10,500 to 10,000 years BP, according to Ledru (1993): the probable rarefaction of tree species, should have provided a decay of root-strength, increasing erosion susceptibility throughout the Bananal basin. The recent cycle of about 200-100years, on the other hand, constituted a geomorphic response to the regional deforestation due to the introduction of extensive coffee plantations.

According to Dantas & Coelho Netto (1995) sedimentation rates along the Piracema valley bottom was on the order of 1,485 m^3/km/year during the Pleistocene-Holocene aggradation cycle; it would correspond to local lowering rates around 1.5 mm/y or 3.0 m/cycle (of 2,000 years), particularly within the topographic hollows (or rampa complexes) as they constituted a major sediment source area. For the coffee cycle, the authors found higher sedimentation rates, on the order of 3,737 m^3/km/y, which correspond to diffusive lowering rates around 0.75 mm/year or 7,5 cm in the last 200 years, throughout the basin area.

The catastrophic geomorphic response to the regional deforestation was associated with severe changes on hillslope hydrology and, consequently, in the mechanic of soil erosion. While in a preserved forested environment overlandflow production is negligible and erosion is mostly related to biogenic mechanisms and slow mass movements (Coelho Netto, 1985, 1987), historical documents from the coffee-cycle report that torrent and muddy flows prevailed during stormy periods. Higher overlandflow and sediment production converging to the river system, probably intensified bed incision into the thick alluvial fills. In effect, post-coffee incision was observed in several tributary valley bottoms of Bananal river, possibly extending over minor tributary channels.

Presently, channel incision (or gullying) is advancing throughout the lower order tributary valleys of the headwater zones, still filled up with hillslope sediments rather than fluvial deposits (rampa complexes). It should be envisaged as a delayed response to the re-adjustment of the regional drainage network. Since the beginning XX century up to now, the spread of cattle grazing over the region has favored gullying processes, again in response to significant changes on hillslope hydrology and mechanics of erosion. Field measurements and experiments demonstrated that vegetation-fauna-soil interactions near the surface favored infiltration capacity (Deus, 1991): grass-roots and the network of pipes constructed by «Saúva» ants[8] provide higher hydraulic conductivity within the dense-root zone of about 30 cm thick. At 10 cm deep, average saturated hydraulic conductivity is on the order of 1.26 x 10^{-4} cm/sec, while at 30 cm and 60 cm it decreases to around 3.52 x 10^{-5} and 4.45 x 10^{-5} cm/sec, respectively (Cambra & Coelho Netto, 1998).

Soil excavation by «Saúva» ants reach an adult age in ten years; at this time interconnected pipes of variable diameter (millimeters to few centimeters) extends radially from the central mound up to 400-500m distant apart, and vertically to about three meters deep. Deus (op. cit.) observed that soil structure is strongly excavated in the Bananal area: reproduction rate is on the order of two to three anthills per hectare per year. The author also noticed that pipeflow may generate whenever the soil surface reaches a nearly saturation condition, whence the recharge of a temporary saturated zone, particularly at the base of the highly permeable Quaternary deposits along the main valley axis. Gullying connected to the regional network is primarily associated with the exfiltration of such temporary subsurface flows as will be discussed ahead.

Present-day erosion: mechanims and major functional elements

Field measurements and experiments have been concentrated in the Piracema sub-basin to provide a better understanding on gullying mechanisms and major functional elements controlling network growth, as will be summarized here. Main works include: Coelho Netto & *alii* (1988); Coelho Netto & Fernandes (1991), Oliveira & *alii* (1994); Cambra (1994) and Coelho Netto (1997). In the Piracema sub-basin, most gullies developed in connection to the regional channel network (83%, for N=117), among which 52% are stabilized and 31% are active; the other 17% of observed cases developed in separately, along minor topographic hollows of the headwater zones (tab. 1).

TABLE 1 - Gully frequency in the Piracema river valley: (S) stabilized; (A) active and (D) disconnected from the channel network (N = 117).

Valley side	S (nr)	A (nr)	D (nr)	Total (nr)
Left	44	15	7	66
Right	17	21	13	51

Gullies developed over distinct lithologies, being more frequent (56.5%) in the left side of Piracema river valley: while 37.6% of cases have been already stabilized, 18.9% are still activated, as shown in figure 17. On the contrary, in the right valley side active gullies prevail (18%) over the stabilized one (14.5%) indicating a relative later response to the re-adjustment of the drainage system. Also in the right valley side occurs the highest frequency (11%) of gullies separate from the regional network. Such spatial variations seem to reflect the average lower topographic gradi-

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[8] According to Deus (1991) the work done by «Saúva» ants, at Bananal basin/Bela Vista amphitheater, connect the surface to soil depth through a couple of thousand micro holes (mm to cm) and pipes of variable diameter up to 2-3 m deep.

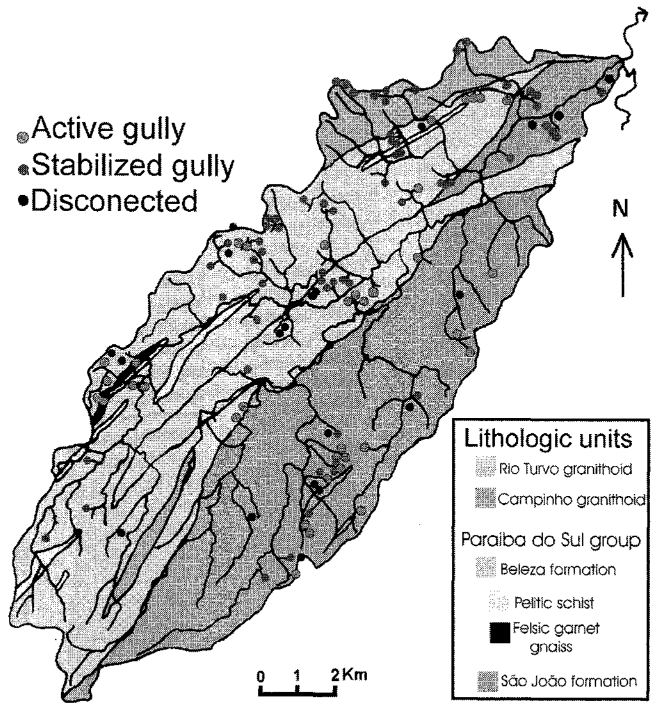

FIG. 17 - Lithological background and gully distribution in the Piracema river valley: green mark is active; red mark is stabilized and black mark is disconnected from the channel network.

ent in the right side of the valley, as it stands at hanging due to successive bedrock knickpoints upstream from the bifurcation with Manso creek. Another aspect to be considered should be related to the spatial variability of the underlying sub-vertical joints, as previously observed by Avelar & Coelho Netto (1992a).

Gullying expansion connected to the regional network has been measured since 1982 at Bela Vista amphitheater described earlier (fig. 18). The selected gully progressed from the right banks of Piracema river through the axis of a major topographic hollow and then, growing finger-tips toward the upper, minor hollow axis (see figure 18 - bellow/right). The main trunk and its minor tips developed parallel to the underlying sub-vertical joints, as indicated in Figure 16-bellow/left. So the typical «narrow-end» shape of Bela Vista amphitheater, together with its joint-controlled channel network, was considered to be representative for Bananal drainage network as a whole.

Gully retreat for the total measured period (1982-1997) was on the order of 1285.5m^3/year. Average monthly erosion rates tend to increase linearly with average monthly rainfall. Tip 1 and tip 2 (see location in figure 18-below/left) have shown similar behavior until December/85; then, erosion rates increased at tip 2 which has been retreating faster and faster as it gets closer to the watershed divides. Similar tendency was observed at tip 3, while tip 1 maintain the lowest retreat rate for the last years (tab. 2).

TABLE 2 - Erosion rates (m^3/year) and physical aspects of respective source areas in the Bela Vista amphitheater: total and mean monthly rates in the main trunk (A) and main headzone (B) from 1982 on; average monthly rates at tip 1 (central); tip 2 and tip 3 (minor finger tips); MMR is mean monthly rainfall (from Coelho Netto & *alii* 1988; Coelho Netto, 1997).

Site	Nov/82-Jan/84	Jan/84-Dec/85	Dec/85-Jan/87	Jan/87-Jul/94	Nov/82 Jul/94	Jul/94-Apr/97	Area (10^3.m^2)	Gradient m/m^2	Hollow density (m.m^{-2})
A	6,227.0	1,062.8	408.1	1,248.4	—	1,948.9	160	0.4	0.01
B	909.4	216.4	961.7	477.2	—	1,537.7	88	0.2	0.01
A + B	7,136.4	1279,2	1,369.8	1,725.5	—	3,486.6	—	—	—
average/ month	509.7	55,6	105.3	19.2	—	105,6	—	—	—
Tip 1	28.0	3,8	20.6	1.3	6.1	11.61	59	0.23	0.01
Tip 2	27.1	2,4	58.0	3,9	11.0	32.6	11	0.22	0.04
Tip 3	—	—	—	—	8.0	46.2	8	0.30	0.04
MMR	148.2	101.5	136.7	121.38	122.2	—	—	—	—

Among the physical aspects of the source areas converging to their respective gully heads, hollow density[9] (Hd) seemed to be the only morphological parameter fitting well with the spatial variation of erosion rates, as shown in the same Table. To evaluate the role of «hollow density» in controlling gully retreat, topographic measurements were made in several gullying-valleys of Piracema river sub-basin. Oliveira & *alii* (1994) confirmed that gully length increases linearly with total hollow density within the amphitheater; in addition, the distance between the gully head and the watershed divides is inversely proportional to hollow density above the channel heads, as shown in figure 19.

Gully formation and network growth followed the «headward spring sapping» model stated by Dunne (1980,1990). Gullying connected with the expansion of the regional network occurs in two major phases: phase 1 is associated with the removal of the Quaternary sediment fills and phase 2 is related to the progression of channel incision into the saprolite (fig. 20) Above. Initially, river incision exposes a seepage face at the base of the thick, loose and highly permeable Quaternary alluvium-colluvium; exfiltration of temporary subsurface flows may attain critical discharge particularly at the confluence with tributary topographic hollow axis, envolving seepage erosion and tunneling; as tunnel excavation progresses headward the roof tend to collapse; the mechanism will repeat itself since the collapsed materials are removed from the seepage face, especially by washing processes and bank scouring.

Once the Quaternary fills are removed, channel incision may progress into the saprolite and reach the regional aquifer; lateral and backward retreat rates tend to accelerate; when it gets closer to lateral slopes, it may trigger landslides. Extensive landslides usually show a well-defined zone of slip surface in association with clay-rich saprolite bands (in the hilly compartment) or soil-rock boundary (in the mountainous compartment). The first case is exempli-

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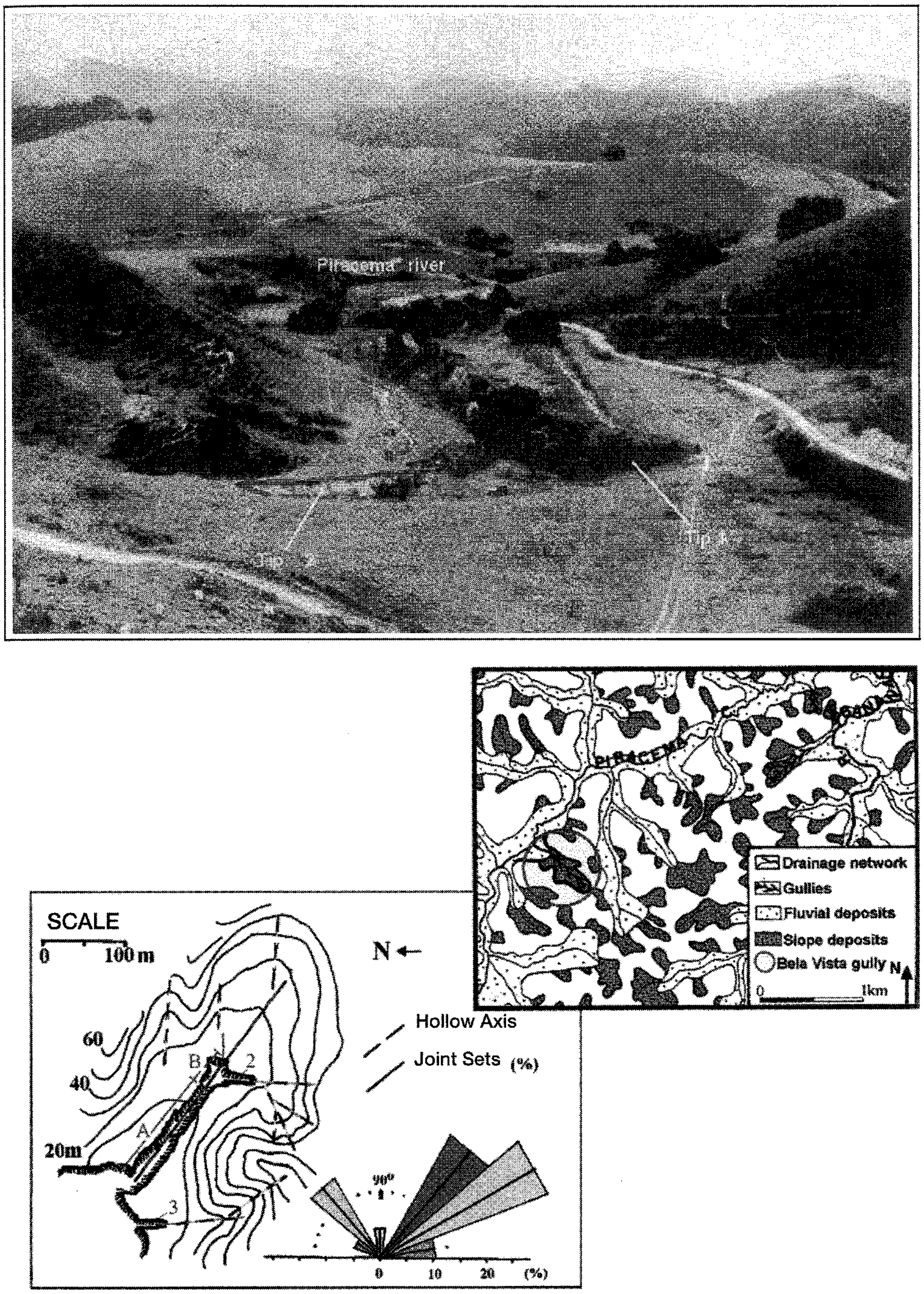
[9] Hollow density was defined as being the total length of hollow axis above channel head, over the contributing source area – Hd = L/A.

FIG. 18 - Field view of Bela Vista gully connected to Piracema river; below/right-location map; below/left-topographic map and local joint-rose.



fied in figg. 21 and 22. In this observed case, differential weathering in the well-banded Tres Barras gneiss provided a layered saprolite with visible hydrologic and mechanical discontinuities. So temporary saturated zones may occur right above an impermeable quartz-band as shown in figure 21; the saturated layer is rich in weathered feldspar (caolinite) favoring the slip surface. The second case is illustrated in figure 23, at Fortaleza area. Landslides started to occur in association with channel incision following the local sub-vertical joints and has already progressed beyond the watershed divide. Mass movements and slope retreat tend to progress in association with gully expansion, particularly when critical pore-pressure and decreasing strength act during extreme rainfall events.

In figure 20-below we sketched a complete sequence illustrating the headward progression of the channel network by the compound action of temporary and regional groundwater flows, as described for incised channels con-

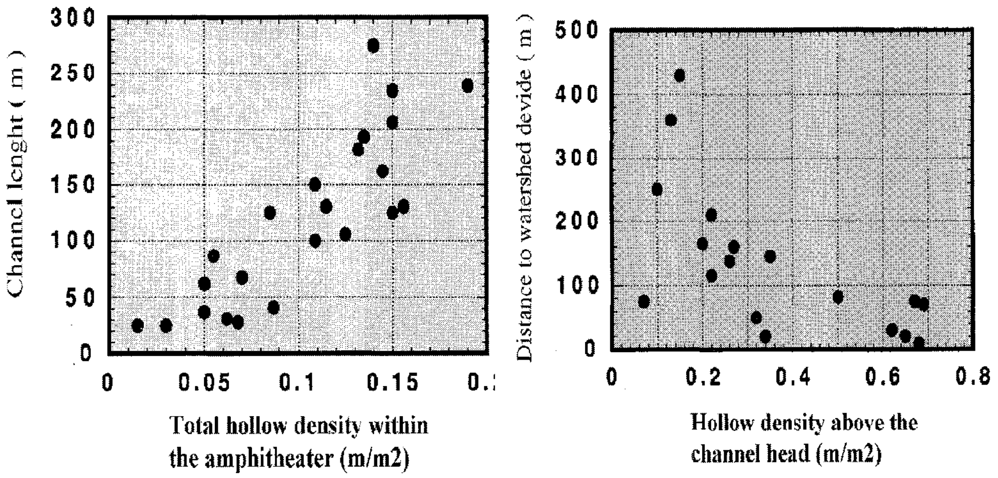


FIG. 19 - A) Relationship between total hollow density within low-order amphitheaters (m/m^2) and channel length (m) at Piracema river sub-basin; B) Relationship between hollow density above channel heads (m/m^2) and distance to watershed divides (m) at Piracema river sub-basin (modified from Oliveira & *alii*, 1994).

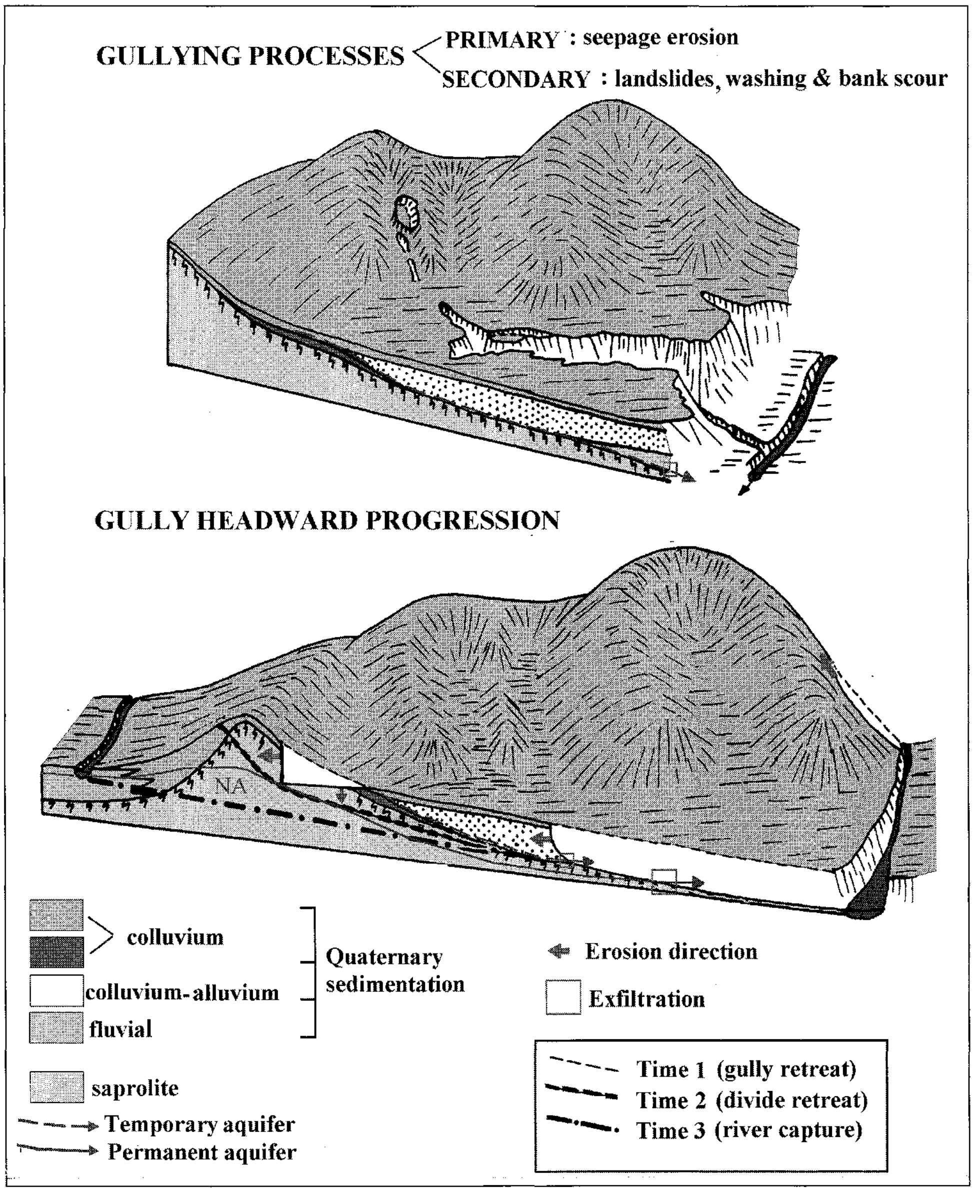


FIG. 20 - Above) Sketch diagram indicating the primary mechanism of gullying in association with exfiltration of temporary groundwater flows at the base of the Quaternary deposits; Below) Headward progression of gullying connected to the regional network and disconnected, both of which may interconnect or not; as channel incision reachs the regional groundwater and progresses onto the saprolite, erosion rates tend to accelerate; gullying may advance beyond the watershed divides causing relief inversion (as indicated by the colluvium in the present watershed divide); it may also leads to capturing, especially when adjacent to hanging valleys due to bedrock knickpoint (downstrem the captured valley).

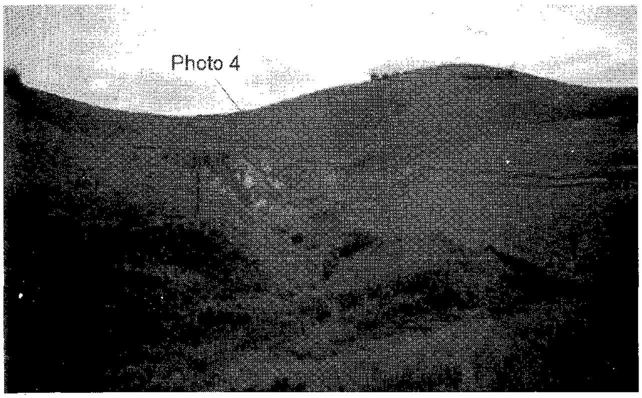


FIG. 21 - Landslide triggered by gullying connected to the Bananal river at Gabrielzinho site in the hilly compartment: as channel incision progresses, landslide moves down and open a trench in the backside. Location of fig. 22 within the red square.

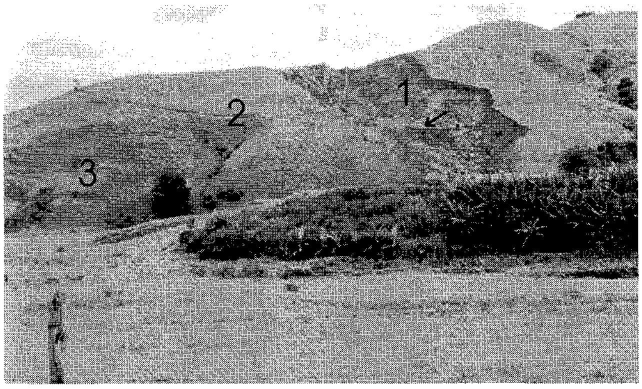


FIG. 23 - Landslide triggered by gullying connected to Fortaleza creek in the mountainous compartment: the slip surface is associated with the soil-rock boundary (1). On the left side of the landslide, one can see a minor channel initiation by seepage along joints (2) and, on the extreme left side, a minor slump in connection to bank scouring which may originate a broad-shallow topographic hollow (3).

nected to the regional network. Connected channels may or may not interconnect with minor gullies developed separately, as previously observed by Oliveira & Meis (1985). As the gully heads approximate the watershed divides of a typical joint-controlled amphitheater, gullying is operated by artesian flows from regional groundwater aquifers. Seepage erosion and landslides (especially of slump type), together with subsequent erosion onto the erosive scars (by washing processes and short-distance debris flows), can lead to slope retreat beyond the original watershed divides, as shown in figure 24. Gully retreat may propagate headward and capture an adjacent river valley, particularly hanging ones, due to bedrock knickpoints downstream: differences in elevation of their respective water-tables would favor groundwater piracy by the capturing gully, feeding critical discharge to propagate seepage erosion backward.

FIG. 22 - The slip surface associated with a quartz-band at Gabrielzinho site.

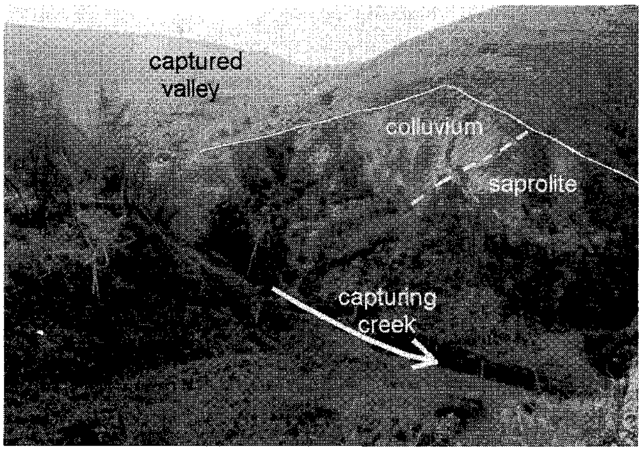


FIG. 24 - Slope retreat beyond the watershed divide and capturing of an adjacent hanging valley: notice the colluvium in the present watershed divide indicating the relief inversion. The capturing channel is a tributary of the Barreiro de Baixo river and the captured one is the hanging Campo Alegre valley, which is drained by its main tributary channel.

As channel incision progresses at grade or hanging in relation to the adjacent valley bottom, hillslope amphitheaters (or rampa/rampa complexes) may develop. Slope retreat within the rampa complexes envolve pedimentation at local scale which may expand beyond the watershed divides due to the coalescence of rampa complexes, as previously described. The hilltop declines as the watershed divides move backward and coalesce. Independently of their specific topographic aspect (at grade, hanging or coalescing) the spatial distribution of structurally controlled rampa/rampa complexes vary along the Bananal-Piracema interfluve, as indicated in table 3.

Excluding the non-structural cases («broad-shallow»), hollow density increases from the serra da Bocaina towards to Paraíba do Sul river. Structurally controlled hollows at grade with the adjacent valley bottom predominate (53 %); together with structural hanging hollows, and coalescing hollows, they represent 74.6 % of observed cases (N=720). It means that slope retreat and pedimentation tend to be more effective downvalley of Bananal basin, especially within the structurally controlled rampa complexes. This frequency distribution is probably responsible by the origin of the gentle inclined pedimentary surfaces as suggested by the average hilltop altitudinal profile, shown in figure 3.

TABLE 3 - Frequency distribution of distinct hollow types along the Bananal-Piracema interfluve: A, B, C and D are equal areas from the serra da Bocaina to Paraíba river.

Hollow type	Area A	Area B	Area C	Area D	Total
Non-structural	49	47	40	47	183
Structural/hanging.	16	9	11	20	56
Structural/at grade	71	74	74	162	381
Struct./coalescing	22	15	16	47	100
Total	158	145	141	276	720

Evolutionary pattern of the Bananal river basin: space and time

Field data and observations brought into view that inherited tectonic, climatic and human induced changes interact and provide variable functional structures that govern landscape modifications over space and time. Since the Early Cenozoic diastrophism, the energy gradient has been renewed and has driven forward landscape evolution in the Bananal river basin, as summarized in the diagrams of figure 25.

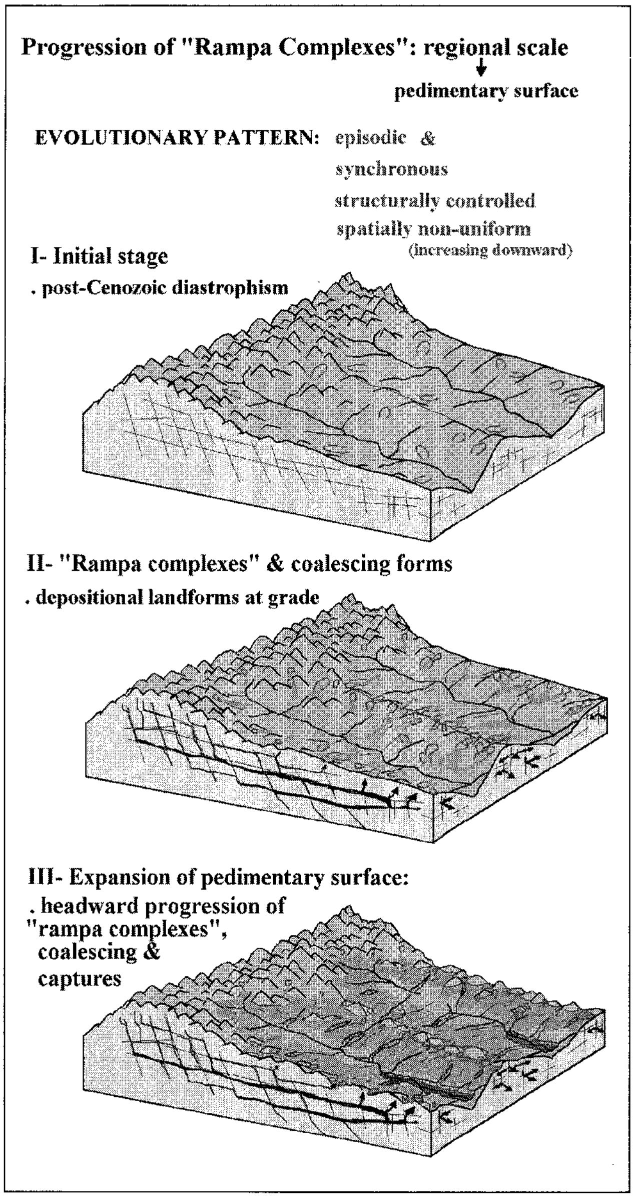


FIG. 25 - Scheme of the spatially non-uniform, episodic and synchronous evolutionary pattern of the Bananal river basin: successive generations of rampa/rampa complexes and development of pedimentary surface.

Inherited geological structures and delayed ecosystemic responses to climatic transitions from cool/drier to warmer/wetter conditions, have been controlling groundwater hydrology and consequent erosion mechanics. The regional increasing frequency of intense rains over weaker-resistant soil mantles, yet covered by sparse vegetation from the previous drier climate, would explain the erosion-deposition episodes over geological times at a basin scale. Intense erosion rates led to gullying, connected or not with the regional channel network, and catalysed the development of rampa and rampa-complexes in the headwater zones, most of which under strong structural control by joints and rock bedding.

As channel incision and slope retreat progressed over the headwater zones and increased the topographic hollow density, erosion rates and gully retreat became more and more effective. Despite a number of successive degradation/aggradation cycles, land sculpture did not mask the parallelism between the orientation of channel reaches or topographic hollow axis and the strike of sub-vertical joints. So the spatial pattern of the drainage network still reproduces the preferential groundwater flow routes at different hierarchical levels of the drainage system.

Present-day gullying is in true an exhumation of older Pleistocene channel routes, previously controlled by geological structures inherited since ancient times. Once dissection reaches again the saprolite and the regional groundwater exfiltrates, structurally controlled gullying accelerate and new amphitheater-like landforms may be added to the landscape. On the other hand, joint controlled bedrock knickpoints sustain a succession of hanging valleys which favor groundwater piracy by gullying connected to lower baselevel controls. Under such condition, erosion may propagate beyond the watershed divides, giving origin to coalescing landforms or capturing adjacent river valleys. Slope backward or lateral retreat leave behind local pedimentary surfaces over which aggradation and degradation cycles alternate episodically.

Whenever thick sediment fills drowned the topography, a grade condition might have been sustained throughout the warm/wetter periods, under the dominance of the Atlantic rainforest environment. During such relative stable periods, gradual channel incision would tend to prevail, as previously stated by Bigarella & *alii* (1965) and later supported by Coelho Netto (1985). Climatic fluctuations toward relative drier climates would promote the rarefaction of tree species, increasing erosion susceptibility. So in the next transition to warmer/wetter periods, marked by an increasing frequency of intense rains, new episodes of intense erosion rates would tend to modify the landscape: firstly emptying the valley bottoms (lowering baselevel) and exposing seepage faces under critical discharge, and then, initiating channel incision to re-adjust the channel network and catalysing new rampa generations or reworking the oldest one.

As slope retreat accelerates near the watershed divides, coalescing rampa/rampa (fig. 26) complexes would tend to feed a new aggradation cycle yet in the transititory environment, until a new adjusted environmental condition is reached, as following: a) giving rise to thick sediment fills to bury again the seepage faces; b) reducing the topographic compartments and gradients as the valley bottoms are raised; c) fully return of the dense Atlantic rainforest decreasing erosion susceptibility and d) increasing water storage and losses by evapotranspiration. Under the dominance of the Atlantic rainforest, channel incision might have evolved gradually. As the forest cover rarefied due to climatic or human induced changes, erosion rates would intensify in response to the increasing frequency of intense rainfalls during warmer/wetter periods, bringing back a new aggradation cycle and repeating the sequence above.

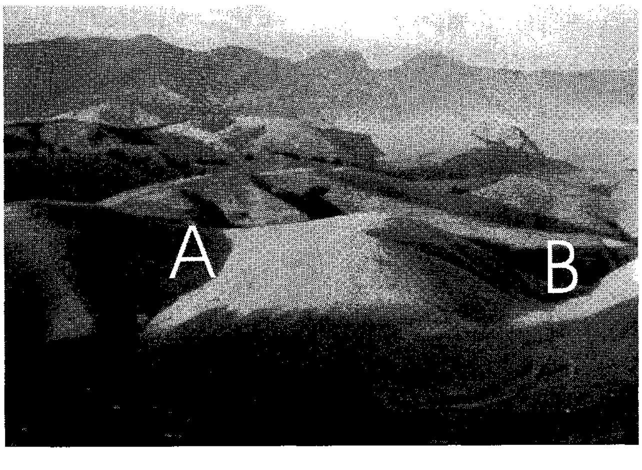


FIG. 26 - Morphological features of relief inversions within rampa complexes: A) caused by the retreat of watershed divide; B) caused by the coalescence of adjacent rampa complexes.

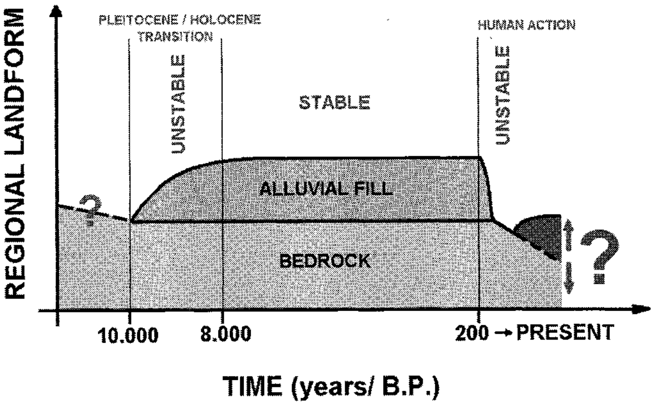


FIG. 27 - Regional scheme of landscape evolution alternating unstable-stable morphodynamic periods in response to climatic induced environmental changes of the Pleistocene-Holocene transition and, more recently, in response to human induced action.

The available stratigraphic records and dating pointed out two consistent Late Quaternary aggradation cycles, besides the sparse Pleistocene lag deposits: one in response to the Pleistocene-Holocene environmental transition and the other in response to forest devastation by human action (fig. 27). From these records we also learned that aggradation did not advance backward from the lower Bananal river valley to the mid-upper one, as it might be expected. Aggradation raised synchronously all over the basin, indicating that the erosive process-operations envolved the drainage basin as a whole. So the downvalley increasing of hillslope dissection is not time dependent but it is probably related to the higher probability for groundwater flows to intercept the surface by artesian flows.

Once more the spatially non-uniform removal of thick sediment fills is in progress: while gullying has already progressed and is stabilized in certain places, in others it is activated and progressing deep into the saprolite; in other places the valley bottoms still remain drowned. It is probably a question of energy availability, particularly associated with the underlying geological structures and local capability for generating artesian groundwater flows. Until gullying starts and progresses to a certain point, hillslope denudation will be restricted to sparse and non-structurally controlled erosion processes. In the near future only sparse lag deposits will remain stored within the basin, as it happened with the Pleistocene statigraphic records, which are not sufficient to tell us the full story of older geomorphological cycles. So, what is the current direction of geomorphologic work? What prevail nowadays under accelerating human interference over the landscape composition and structuring? Probably a new aggradation cycle is just starting, at least in the Bananal river basin.

CONCLUSIONS

How far does the Bananal model apply?

Before extrapolating the Bananal model throughout the Southeastern Brazilian plateau and coastal lands, we drove our attention toward the middle Paraíba do Sul river valley for comparison. We just crossed the big river and visited a neighbor drainage basin – the Turvo river basin, which drains the faulting scarps of the serra da Mantiqueira toward the Paraíba river at the Volta Redonda transfer zone (see location in figure 28).

Climatic conditions are quite similar, as much as the recent land use history. Present land use is mostly associated with cattle grazing and «Saúva» ant is the predominant soil-fauna. The underlying bedrock is highly jointed and fractured, in association with normal faults of Cenozoic age striking ENE and dipping to SE; other transcurrent faults of same age are striking NW-NNW, as indicated in figure 28. The Turvo river runs parallel to major normal faulting scarp, while Pedras river and respective subtributary channels are dissecting along the transcurrent faults, orthogonal to the major one. The hypsometric map delineates two main topographic compartments: the mountainous, dominated by faulting scarps on Precambrian rocks of the Andrelândia depositional cycle, which constitute the allocthonous middle tectonic compartment; the hilly convex-concave lowlands is dissecting into the upper tectonic compartment of the Paraíba da Sul Group. Dissection into Precambrian rocks did not form wide valley bottoms as in the Bananal basin. In the lower valley, the main channels are dissecting into Tertiary sedimentary rocks of the Resende basin, being only slightly developed.

Despite the strong bedrock control in the main channel network, the headwater zones are quite different from the

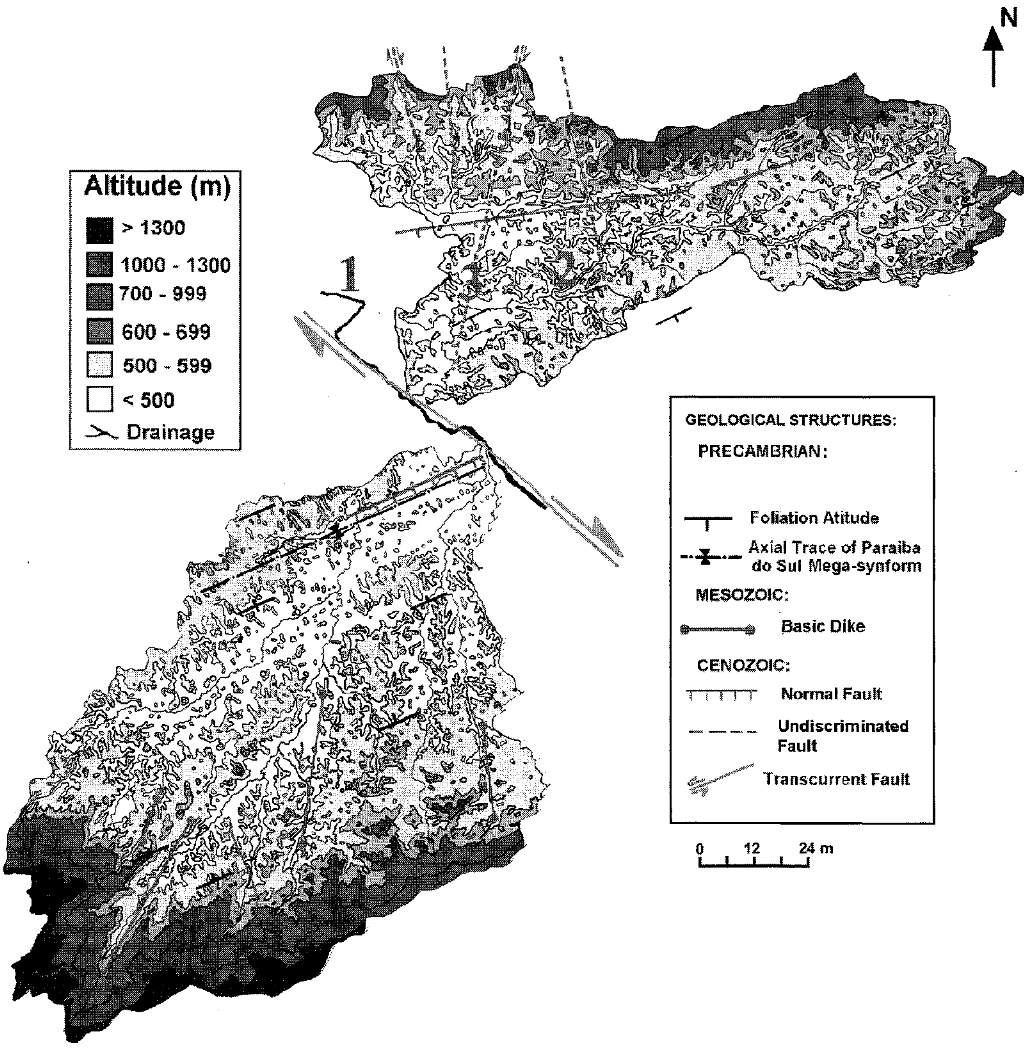


FIG. 28 - Bananal and Turvo river basins: hypsometric maps and geological structures. 1) Paraíba do Sul river; 2) Turvo river and 3) Pedras river.

Bananal drainage basin. Surprisingly, joint-controlled rampa/rampa complexes are rarely found. On the other hand, non-structural amphitheaters with broad-shallow shaping predominates. The underlying bedrock structures' seems to play a different role in controlling the internal dynamic of groundwater flows: at least artesian flows are not generated through the sub-vertical joints to provide seepage erosion and channel initiation. The restricted operation of such mechanism-chain would imply in a relative lower sediment production within the Turvo basin, especially for reducing the probability of slope retreat beyond the watershed divides until coalescing adjacent rampa complexes.

Therefore, hillslope erosion seems to progress under relative lower rates in comparison with the Bananal drainage system and is mostly associated to the mechanism-chain that shaped and yet shapes broad-shallow topographic hollows or non-structural rampa-complexes. In effect, sediment storage along the main valley bottoms is visibly lower than in the Bananal basin and the present channel network seems to be relatively stable, as no active gullies can be found, even in the headwater zones. Facing so many new questions, we decided to initiate field researches in the Turvo basin in order to understand the internal operation of the system and compare it with he Bananal drainage system.

Why Catastrophic?

Episodic landscape evolutionary pattern has been naturally related to climatic induced transitory environments, especially when intense rains have reached a rarefied vegetation cover still associated with antecedent drier climatic conditions or with human intervention. It means that erosion rates tend to mirror the degree of the internal adjustment of the geoecosystem in response to variable energy supplies. However it may vary spatially as a function of the interaction between rainfall characteristics and landscape structures at surface and subsurface, as demonstrated for the Bananal basin scale and also for the middle Paraíba do Sul river valley, that is regional scale.

As we learned in the middle Paraíba do Sul river valley, catastrophic geomorphic responses were typically associated with deforestation at regional scale. Extensive coffee plantations introduced significant geoecological changes, affecting the soil-plant hydrology, especially by lowering infiltration capacity. Thus, larger amounts of eroded sediments by hortonian overlandflows converged into the channels during stormy periods: in a first moment higher stream water discharge might have favored bed incision along the main river valleys and then, as larger amounts of sediments converged to the main channels, the inserted sediment fills accumulated at rates around 3,800 m^3/km/year.

Very recently we assisted to another catastrophic event in the upper portion of Tijuca massif. The very extreme rainfall intensity of February 13-1996 was spatially non-uniform. The most rainy area was located in the uppermost, western-portion of Tijuca massif. A local raingauge station recorded two major storms: first, in the morning (reaching 150 mm in approx. 4 hours), and the second one, in the evening (reaching 230 mm in approx. five hours; with maximum intensity/hour of 50 mm between 19:50 and 20:50 h). The first one triggered several minor landslides along the Canoas and Furnas roads (southern slopes). Catastrophic landslides spread simultaneously in response to the second storm (around 20:40 h.), initiating very close to the crest-zone or near the shoulder of lower interfluves. Extensive rock debris avalanches (> 4 km length) reached the adjacent baixada of Jacarepaguá, causing serious environmental damages, property losses and deaths (fig. 29).

Cumulated rains since July/95 were also exceptionally high. Applying the Guidicini & Iwasa's coefficients[10] we found Cc = 1.064, Ce = 0.175 and Cf = 1.239, fitting well within condition «A»-of higher hazard condition. Nevertheless landslides sites were spatially non-uniform within the western Tijuca massif, mirrowing the role of local environmental conditions in controlling slope stability at a certain place, or providing an increasing susceptibility for landslides. From aerial-photos (1:10000) coupled with field observations we have distinguished some landscape-elements that might have affected the spatial pattern of landslides scars, as described bellow.

In the crest zone affected by landslides, between Papagaio peak and Taquara hill, one finds the dominance of highly jointed, granite rocks and many in situ blocks are hold by tree roots. Draining down the crest-zone toward the Cachoeira river, in the southern slopes of Tijuca massif, only few landslides cases occurred . This is probably associated with two aspects: 1) the forest vegetation is well preserved (Tijuca National Park); 2) the upper Cachoeira is a hanging valley; its average slope gradient is around 18° and other minor hanging plateaus occur. Landslides did not propagate far away apart from their initial places: coarse debris load (blocs, soil and trees) remained stored in the slope domain.

In the western mountain-slopes, largely affected by landslides, we observed that long and steeper slope profiles prevail; vegetation is highly degraded and thus, root-strength has been reduced. In effect, around 42% of landslide scars (> 500 m^2) are surrounded by degraded forest cover (less dense; high trees become sparse) or by grass cover (43%), as shown by Oliveira & *alii* (1996). These authors found that 193,000 trees were lost. Cruz & *alii* (1998) observed reactivation around older landslide scars, from February 1988. The authors suggest that clearing sites due to landslide scars provide micro-climatic changes

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[10] Guidicini & Iwasa (1977) found that rainfall events above 250-300 mm are able to trigger landslides in all conditions. To predict landslide hazards, they proposed the so-called «coefficient of cycle» (Cc = cumulated rainfall (mm) until the intense rainfall event / mean annual rainfall (mm), and «coefficient of episode» (Ce = rainfall event (mm) / mean annual rainfall (mm). The sum of Cc and Ce, called «final coefficient» (Cf), plotted against months of the year indicate four conditions for landslide hazard (A, B, C and D). Condition «A», represents the higher landslide hazard: the amount of cumulated rainfall attain higher values than the mean annual precipitation, in association with intense rainfall.

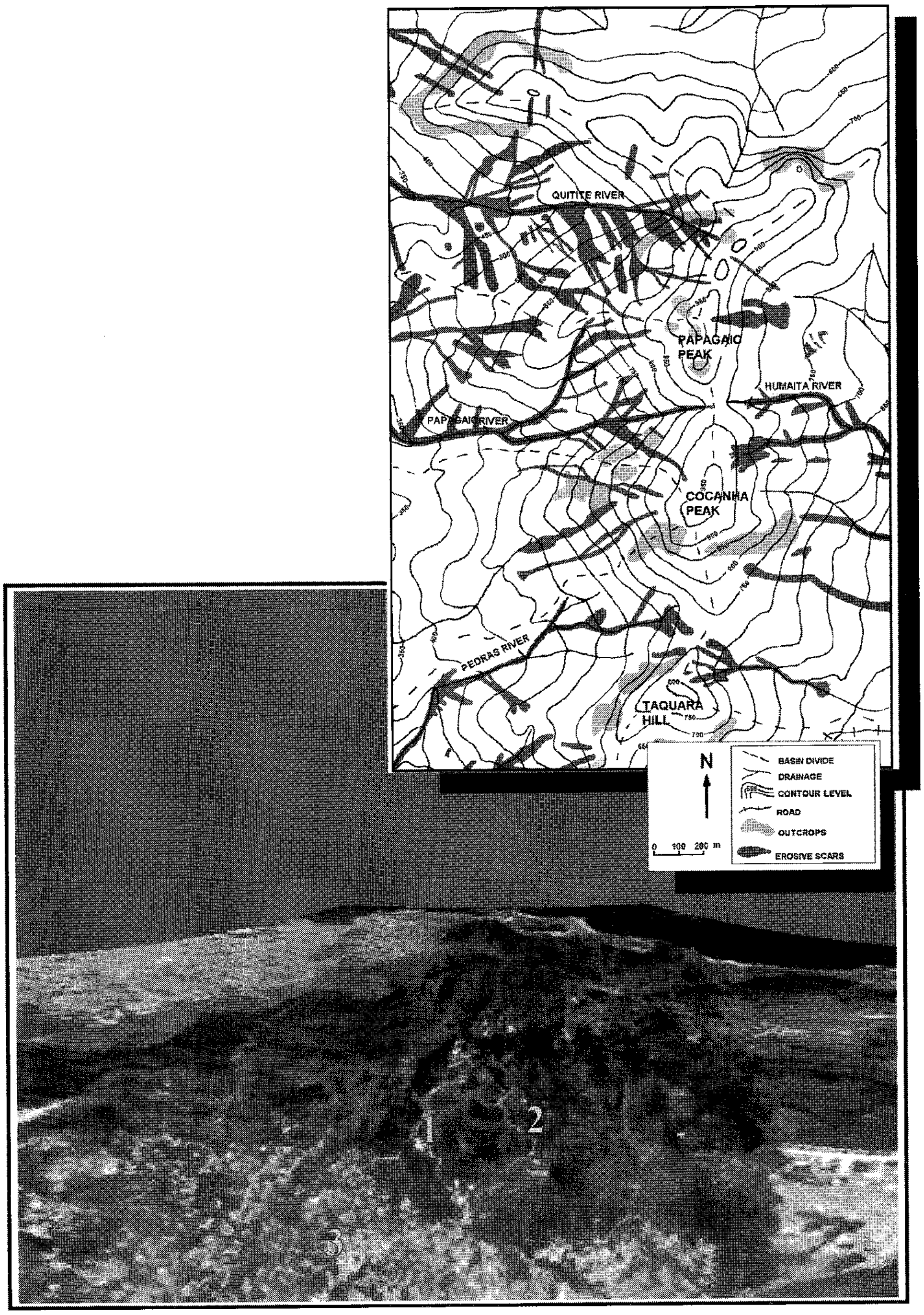

FIG. 29 - Location of debris flows initiation near the peaks of Tijuca massif in response to the very extreme rains of February 13, 1996: extensive rock debris avalanches followed the main channels draining the steeper western slopes toward the baixada of Jacarepaguá; in the eastern slopes, rock debris avalanches were mostly stored within the hanging plateaus and tributary valleys, before reaching the main Cachoeira river. 1) Quitite river; 2) Papagaio river and 3) Baixada of Jacarepaguá.

right on the border, leading to forest degradation and therefore, increasing landslide hazards.

Landslides of debris-flow type prevailed all over the area. Initial mechanisms should be related to two-conditions: mass-shock against the lose colluvium (block-rich) or suddenly increase of pore-pressure (as demonstrated experimentally by Avelar & Lacerda, 1997). Debris flows propagated downslope into the main channels to form extensive rock-debris avalanches. Velocity attained 2.8 to 5.3 m/s as indicated by Vieira & *alii* (1997) These avalanches led to channel incision into the fresh bedrock and left behind wider river channels. The simultaneity of landslides reveals that a certain threshold was reached, before landslides were triggered. In the surrounding baixada lands, river channels became completely drowned and flooding spread all over the area.

It seems clear that only one extreme rainfall event, with highly cumulated antecedent rain (previous 6-months) led to extreme geomorphic responses, as it has interacted with a disturbed environment due to human induced geoecological changes. Erosion-sedimentation rates attained a catastrophic magnitude, not only for its physical dimension, but also for affecting the sustainability of the geo-biodiversity and causing serious socio-economic damages with irreversible human losses. Nowadays erosion susceptibility increased as landslides-clearing sites spread over the steep slopes and border effects again promote forest deterioration. In ten years the forest vegetation will not be fully recovered in their functional aspects that regulate both hydrological and mechanical soil properties, as shown by recent works in the Tijuca massif (Rocha Leão & *alii*, 1996; Cruz & *alii* 1998).

Catastrophic geomorphic responses were detected at different time scales: a) for individual rainfall events over disturbed geoecossystems at the mountain-forest-megacity interfaces; b) for long-term rainfall periods (hundred years) over extensive disturbed geoecossystems at the forest-coffee-cattle grazing interfaces and c) for recent geological times (Pleistocene-Holocene transition) over climatic induced transitory geoecossystems. What do they have in common? Two major aspects: 1) climatic fluctuations toward warmer conditions, leading to an increasing frequency of intense rainfalls and 2) Forest disturbances ranging from subte decreasing of tree species (naturally or artificially) to complete removal. In what aspects the studied geoecossystems differ? Basically in their internal rules governing groundwater flows and their implications with hillslope erosion, particularly at basin scale. So, many questions still remain open to guide future investigations. The more we learn by field investigations, more we realize all aspects that yet remain to be known and understood, at least in the complex geomorphic systems found in SE Brazil.

ABSTRACT: COELHO NETTO A.L., *Catastrophic landscape evolution in humid environments: inheritances from tectonic, climatic and human induced changes in SE Brazil.* (IT ISSN 0391-9838, 1999).

Humid environments comprise landscapes under permanent riverflow regimes, including areas with distinct geo-biophysical and sociocultural conditions as a product of theil respective geological, climatic and human histories. Over time, environmental changes of a certain order of magnitude may shift the direction of landscape evolution leaving bellind degradation/aggradation cycles, sometimes at very intense rates or catastrophically. Therefore humid landscapes are expected to preserve at least some relict features from these cycles, specially on the hillslope morphology and stratigraphical records providing partial arguments for the reconstruction of landscape evolution over space and time. In this lecture I will address questions about the role played by such inherited geological-geomorphological features in controlling present-day processes that govem landscape evolution. Special attention will be driven toward the geomorphic responses to antropogenic environmental changes within an ecosytemic approach.

Field arguments derive fiom researches conducted in SE Brazil, specially in the Paraiba do Sul rivel valley. Following the pleistocene savanna-like environment, this region was dominated by the tropical rainforest (called Mata Atlantica) throughout the Holocene despite minor climatic fluctuations toward to relative drier climatic conditions. Deforestation started in the mid-XVIII century when coffee plantatiolls spread all over the region and remained until the end of the XIX century; then the region was domillated by cattle grazing. As pointed out in the previous work conducted by Meis and hel collaborators, based on detailed morpho-stratigraphic records, hillslope evolution followed a highly discontinuous evolutionary pattern: denudation was concentrated within the so-called rampa complexes (topographic hollows) being submitted to sucessive episodes of higll erosion-depositional rates in response to paleohydrological changes (Meis & Monteiro, 1979; Meis & Moura. 1984; etc.). In the last 20 years we have integrated morphological, stratigraphic and process studies arguments to support Meis's theoly and bring into view a mecanicist explanation of landscape evolution withill an ecossystemic approach. Emphasis has been given to a better understanding on erosion mechanisms and variablecontrols, focusing the geomorphic responses to recent environmental changes. Despite a complex geomorphic history of such Dunnean-Hortonian landscape, present-day processes reproduce the same mechanisms and routes from recent geological times (Late Quatemary at least); the evolutionary pattern have coupled episodicity and synchronization at both hillslope and fluvial degradation-aggradation cycles under high rates; the spatially non-uniforrn hillslope evolution is strongly controled by the underlying litho-structures (fractured, well-banded gneisses & granitoid rocks) derived from ancient times; the regional denudation is therefore governed by local slope retreat and relief inversions due to the destruction of watershed divides; therefore the remnants of older erosion surfaces are gentle inclined as the density of local process dynamic increases from the mountain compartment toward to the hilly lowlands and to the main regional collector, the Paraiba do Sul river.

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