

PALEOSURFACES IN SOUTHEASTERN BRAZIL: SÃO JOSÉ DOS CAMPOS PLATEAU LANDFORM EVOLUTION

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ABSTRACT – Long-standing views on landform evolution in the Brazilian tropics postulated alternation of morphogenetic processes under semi-arid conditions and development of soil covers along warm humid periods. Reassessment of Quaternary chronologies, research on nature of morphogenetic processes and landform and soils surveys led to reconsideration of former models. Data from São José dos Campos plateau ($\approx 200 \text{ km}^2$) (São Paulo, SE Brazil) link weathering mantles and latosolic pedogenesis to warm/humid environments where chemical/geochemical processes contributed to lower the remnants of a Tertiary planation surface. Closed depressions, amphitheatre-like valley heads, and other pseudo-karstic features evolved over Oligocene and Miocene quartz-kaolinitic sediments interbedded with sandstones and pebble layers. Shape, size, and distribution of depressions helped to identify a SW compartment where isolated active depressions and wide level interfluves occurred, a central section with depressions varying in size, shape and distribution, presenting flooded, vegetated, or swampy bottoms, and a NE compartment including few small active depressions in the upper section of small dambos. The appointed differences were related to lithological and/or tectonic discontinuities favoring subterranean water circulation but variations in permeability of sedimentary beds should also be considered. Relationships between geochemical processes and genesis of detailed landforms led to propose the adoption of etchplanation principles.

Keywords: Humid tropical landscapes; Geochemical changes; Landform evolution; Pseudo-karstic features; Subterranean water circulation.

RESUMO – *L. Coltrinari - Paleosuperfícies no Brasil SE: evolução do relevo no planalto de São José dos Campos.* Hipóteses sobre a evolução cenozoica do relevo no Brasil SE sustentavam a alternância de processos morfogenéticos sob climas semiáridos e desenvolvimento de solos sob climas quentes e úmidos. Reavaliações das cronologias quaternárias, pesquisas realizadas na zona tropical úmida no hemisfério sul e dados coletados no platô de São José dos Campos ($\approx 200 \text{ km}^2$) (São Paulo, SE Brasil) vinculam mantos de intemperismo e pedogênese latossólica com ambientes quentes/úmidos onde processos químicos/geoquímicos contribuíram ao abaixamento de remanescentes de uma superfície de aplainamento terciária. Depressões fechadas, cabeceiras em anfiteatro e demais formas pseudocársticas evoluíram sobre rochas sedimentares quartzo-cauliníticas oligoceno-miocênicas interestratificadas com camadas de arenito e conglomerados. A forma, tamanho e distribuição dessas feições permitiram identificar, a SW, um compartimento com interflúvios largos sub-horizontais e depressões isoladas. Na seção central as depressões são numerosas, com dimensões e regime hidrológico variado enquanto no compartimento NE há poucas depressões ativas nas cabeceiras dos *dambos*. As diferenças citadas são em geral atribuídas a discontinuidades tectônicas e/ou litológicas que favorecem a circulação da água em subsuperfície mas sugere-se que a permeabilidade diferenciada das camadas sedimentares seja também considerada. As relações entre processos geoquímicos e gênese do modelado de detalhe conduziram à adoção dos princípios da etchplanação.

Palavras-chave: Paisagens tropicais úmidas, Processos geoquímicos; Evolução do modelado; Feições pseudo-cársticas, Circulação da água subterrânea.

INTRODUCTION

Morphogenetical origin related to semi-arid episodes during pleistocenic ice-ages has been accepted to explain Cainozoic landform evolution in the Brazilian tropics. Until the 1960s only geomorphic data –

morphology and correlative deposits- were considered as a valid basis for landscape evolution models (Bigarella et al., 1961; Bigarella et al, 1965a, 1965b; and others. Reassessment of Quaternary chronologies

and discussions regarding the nature of morphogenetic processes and their relationships with unconsolidated materials covering landforms (Coltrinari, 1992) led to reconsider those paradigms. Data from research on processes acting over and within the soil mantle (Castro, 1989; Filizola, 1993; and others) confirmed the dominance of chemical processes in accordance with zonal climatic parameters and sustained the proposal of a new hypothesis for landscape evolution in southeastern Brazil (Coltrinari & Filizola, 1993) similar to etchplanation.

In the humid tropics landforms in low relief areas include depressions and channeless headwater valleys or *dambos* in central Africa (Thomas, 1994). Previously they were identified as *Flachmuldentäler* by Louis (1957) and “wash depressions” (*Spülmulden*) by Büdel (1957, 1965, 1982). They have been described in Africa (Boulet, 1964; Humbel, 1964; Soubiès, 1974; McFarlane, 1976, among others), in New Caledonia (Trescases, 1975) and in Papua New Guinea (Löffler, 1978). Thomas & Thorp (1980) mentioned evidences of etching and chemical denudation of the basement rock below those valleys so *dambos* could be also degradation forms linked to deep soils and surface downwearing by weathering and chemical erosion.

In south-eastern Brazil depressions and associated features occur either in metamorphic rocks (*serras do Mar* and *Mantiqueira*) or in quartz-kaolinitic sedimentary rocks substratum as in Taubaté basin – where São José dos Campos plateau is located, and were described as *dambo*-like forms developed in

sedimentary terrains by Coltrinari & Nogueira (1989). Their origin was attributed to geochemical processes and compaction of Tertiary clayey beds under swampy areas (Ruellan, 1943; Raynal, 1960; Suguio, 1969; Coltrinari, 1975, and others.). Coltrinari & Nogueira (1989) and Filizola (1993) corroborated the presence of depressions and amphitheatres in interfluves, slopes, and floodplains, on summits and plateau surfaces without iron crusts. Depressions could be dry, waterlogged, or permanently flooded, closed or with uncertain links through shallow valley-bottoms.

Surveying of similarities between amphitheatres and closed depressions showed that sinking is related to rapid chemical erosion and opening is due to lateral flow of perched water table through a lower col after heavy rains that favour the quick drain-off of depressions. The outlet apparently is related to depressions internal dynamics rather than to fluvial capture, the absence of out-flowing streams indicating exportation of weathering products predominantly in solution via macropores or through fractures (Filizola, 1993; Filizola & Boulet, 1996).

The demonstration of geochemical origin of depressions and confirmation of relationships with soil-cover, slopes, and drainage network evolution by Filizola (1993) and Filizola & Boulet (1993, 1996) suggested that mapping of depressions and associated features could be an adequate means to demonstrate the extension and diversity of pseudo-karstic forms in the area, and therefore contribute to support the adoption of a new landscape evolution model for the study area.

MATERIALS, METHODS AND TECHNIQUES

THE STUDY AREA

Depressions and associated pseudo-karstic landforms were studied in the middle upper section of Paraíba-do-Sul river basin located in the Atlantic Plateau (São Paulo State) and hosted in the central segment of the Continental Rift of Southeastern Brazil (CRSB)(Riccomini et al. in Montesso Neto et al.,2004) (Figure 1).

The main stream follows the E-NE trend of the CRSB along its longer reaches turning to NW-SE in orthogonal shorter segments. São José dos Campos plateau is located in the upper section of Taubaté sedimentary basin (SW: 23°10' - 23°18'S & 44°55'W; NE: 23°05' - 23°10' & 44°40'W) and comprises a stretch of hilly landforms developed in quartz-kaolinitic sediments interbedded with, and capped by, coarser layers along the right margin of the Paraíba-do-Sul river.

Geological and Geomorphological Background

The fault-line escarpments of *sierras do Mar* (SE) and *Mantiqueira* (NW) are the boundaries of the Paraíba hemi-graben, a ≈220km long depression partially filled by Tertiary and Quaternary fluvial and lacustrine sediments (Figure 2).

Eocene-Oligocene Tremembé Formation (OstbL) claystones and organic-rich shales outcrop along the Paraíba-do-Sul main tributaries and swampy areas in São José dos Campos plateau. During the Oligocene a fluvial meandering system deposited sandstones, claystones, and conglomerates of São Paulo Formation (OstFM2) outcropping along the plateau SE border and (Campanha, 1994).

In the Miocene the central segment of the CRSB underwent strike-slip regime and structural faulted sills segmented the original rift depression (Figure 1). After the tectonic episodes alluvial deposits from a fluvial

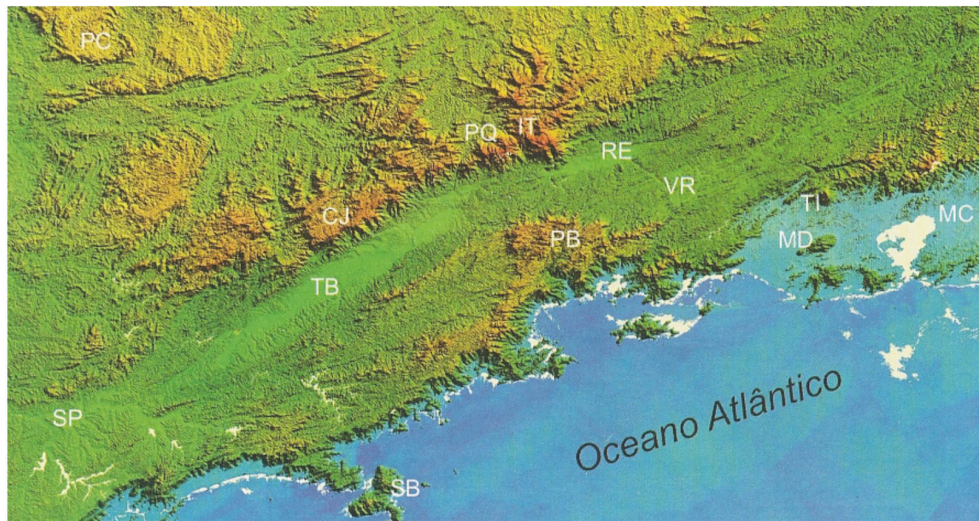


FIGURE 1. Main geomorphological features of the CRBS between São Paulo and Macacu basins in the digital elevation model: São Paulo (SP), Taubaté (TB, Resende (RE), Volta Redonda (VR) and Macacu (MC) sedimentary basins; the Bocaina plateau (PB) in the Serra do Mar, and the Campos do Jordão Plateau (CJ) in the Serra da Mantiqueira; and the Poços de Caldas (PC), Passa-Quatro (PQ), Itatiaia (IT), São Sebastião (SB), Tinguá (TI) and Mendanha (MD) alkaline massifs. Notice the striking ENE to NE Proterozoic basement structures reactivated in the Mesozoic and Cenozoic. Source: Shuttle Radar Topography Mission (SRTM), USGS, 2002. (Adapted and modified from Riccomini et al., in Mantesso-Neto et al., 2004).

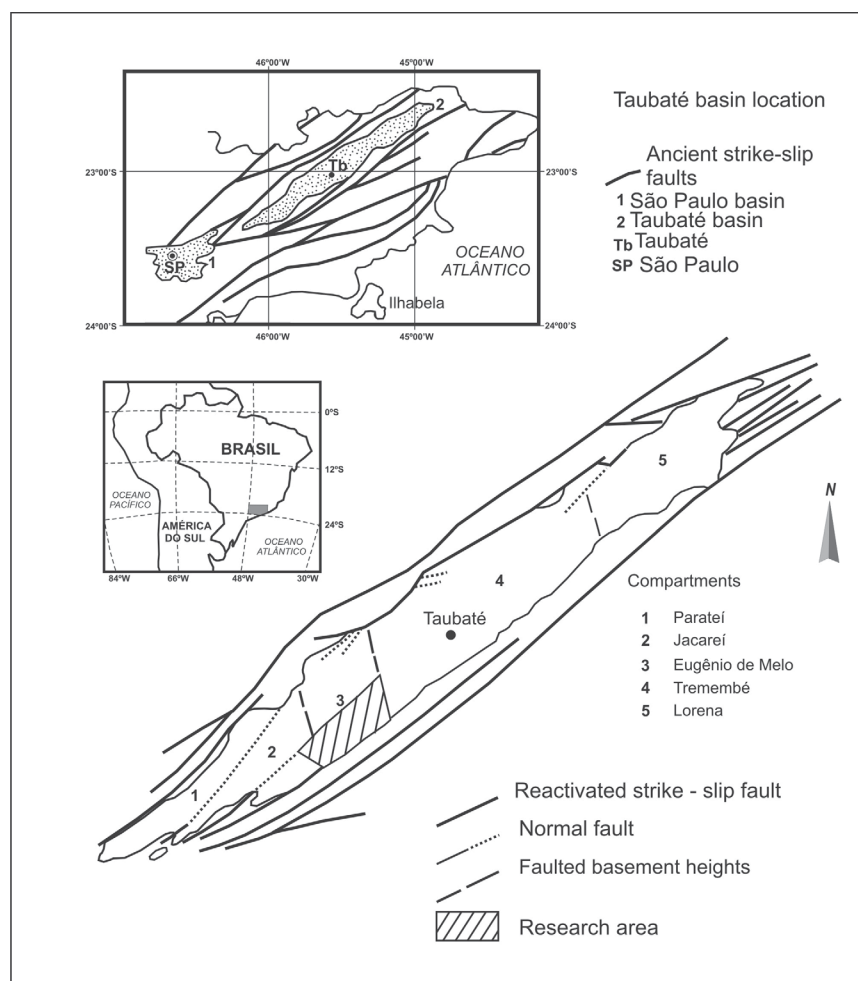


FIGURE 2. Taubaté basin: sub-basins and associated basement structures (adapted Almeida & Hasui, 1984, in Coltrinari, 2003).

meandering system originated Pindamonhangaba Formation (MmFM) conglomerates, sandstones, siltstones, and claystones that outcrop continuously from SW to NE in the Paraíba-do-Sul floodplain and the plateau landforms. Miocene rocks stand out along the SE plateau border and cover discontinuously São Paulo Formation beds particularly in the interfluves between rivers courses flowing from the *sierra* do Mar SW slope. Quaternary sands, clays, and peat deposits appear in floodplains along the main fluvial system while sparse recent conglomerate deposits cap locally Miocene Pindamonhangaba Formation beds.

Landforms examined in this paper were identified in rocks of the middle and upper sedimentary sequences – Taubaté and Pindamonhangaba - that fill the graben (Campanha, 1994). Consideration of stratigraphic information from sedimentary sequences - such as biostratigraphic data and age indication from palynological sequences, allowed the confirmation of a Miocene age for the sedimentary beds supporting the highest summits of the plateau landforms. Based upon species employed to define age and paleoecology both in Brazil (including results from different basins within the CRBS) and other countries, Bistrichi (2001, in Coltrinari, 2003) suggested that Pindamonhangaba sediments in Taubaté basin contained species considered as indicators of Upper Miocene environments.

Extrapolation of Miocene ages to the terminal environment of upper deposits in Taubaté basin and the enhancement of planation processes in that period in the *serra* da Mantiqueira (Bistrichi, 2001) sustain two Campanha's (1994) hypothesis concerning: 1) the attribution of Miocene age to Pindamonhangaba Formation due to its stratigraphic position, and 2) the interpretation of the absence of the original Pindamonhangaba terminal environment as an evidence of truncation of the sedimentary beds by sub-aerial processes.

Data concerning lithology and basement structures are relevant to geomorphological research together with the confirmation by Bistrichi (2001) of a Miocene age for the Tertiary beds identified in the highest summits in São José dos Campos plateau. These informations support the hypothesis that consider landforms (\approx 50 - 700m a.s.l.) in the SW section of the basin as an extension of the level summits (\approx 680 - 750m a.s.l.) of the basement rocks in the SE border of Taubaté basin, where Martonne (1943) identified the remnants of an Upper Tertiary planation surface (Coltrinari, 2003).

In the NE section of São José dos Campos plateau narrower and lower interfluves (\approx 560 - 650m a.s.l.) occur downstream towards the regional base-levels – Paraíba-do Sul floodplain (550m a.s.l) and Caçapava *sill* (540m a.s.l.) – where fluvial dissection and higher

density of pseudo-karstic forms contribute to the break-up of a pre-existent surface (Coltrinari, 1989).

Soils

High percentages of kaolinite in ferralsols and underlying ferralitic profiles point to a high leaching humid or sub-humid environment with coincident warm period and rainy season. Studies concerning the evolution of the pedologic cover in São José dos Campos plateau (Filizola, 1993) suggest that original sand beds were probably transformed into sandy/clayey materials through clay neo-formation and concomitant processes that led to extensive *in situ* evolution of red-yellow ferralsols (Filizola, 1993). Geochemical changes (weathering, mineral neo-formation, and mass loss) related to internal water circulation (slopes base level) are globally considered as agents of landform evolution through vertical exportation of solutes equivalent to processes acting in true karstic areas.

THE MORPHOLOGICAL MAP

Materials and Techniques

Elucidation of geochemical origin of depressions and related features in São José dos Campos plateau and evidences of their relationships with soil cover, slopes, and drainage net evolution suggested that cartography could be a means to show diversity and extent of pseudo-karstic landforms.

The basis for this essay on paleo-morphological cartography was an aerial survey (calculated scale \approx 1:25,300) taken by the Brazilian Army around the late 1930s and deposited in the Remote Sensing Laboratory of the Department of Geography (São Paulo University) since the decade of 1960. From the original collection of 54 vertical photographs only 40 are presently available, many of them seriously damaged because of inadequate storage and conservation. The sequence covering the study area (14 photos) was complete showing only minor damages along the borders. A Zeiss pocket stereoscope was employed for photoanalysis and a mirror stereoscope for the complete vision of each stereo pair. Field descriptions, maps, horizontal photographs, among other resources helped to complete, confirm and/or modify results from basic photo-interpretation due eventually to flaws in photographs. Overlays on Regmaphane polyester paper was transferred first to a horizontal planimetric map and then adjusted to a UTM grid. The legend was partially adopted from St. Onge (1968), Doornkamp & King (1971), and Demek (1972).

Results

São José dos Campos plateau morphological map (Figure 3) depicts landforms presently destroyed and/

or obliterated in the SW extremity of Taubaté basin and confirms the predominance of pseudo-karstic features in the research area.

Considering the height and morphology of interfluvies and in a subordinate level, form size, and distribution of depressions and slope morphology three areas were identified:

1. SW: from Vidoca* (SW) river to the left margin of Alambari* river (NE) (*see morphological map - Figure 3);
2. Central: between Alambari and *Santa-Catarina rivers, and
3. NE: from Santa-Catarina river to the north-eastern end of SJC plateau.

In the SW sector dry, flooded, waterlogged, and vegetated depressions occurred on wide flat tops $\approx 600 - 625\text{m a.s.l.}$ Doline-shaped features drained by ditches and/or by natural outlets turned apparently into headwaters amphitheatres or artificial lakes; they could be circular or elongated as those in the interfluvie Vidoca - Putins. On flat surfaces - valley-bottoms and interfluvies - occurred remnants of dry, round/oval

concave forms surrounded sometimes by low-gradient slopes limited upslope by convexities. Together with segments of shallow dry valleys and traces of concentrated flow remnants of inactive depressions were associated with permeable rocks of São Paulo and Pindamonhangaba formations in this research.

In the central section large flooded depressions ($\approx 590\text{m a.s.l.}$) within round-to-oval amphitheatres arranged along a SW - NE axis fed seemingly Alambari river and its tributary by the right margin. The diameter of former active depressions could reach $H^{\circ} 250\text{m}$; dry concavities were smaller and shallower. The lower courses of small fluvial systems flew probably through swampy areas or drained larger depressions linked probably upstream to smaller dry hollows in a higher level while natural or artificial outlets connected them with streambeds where artificial canal cuts concentrated flows within ill-defined valley bottoms. Those landforms were located in lower interfluvies ($\approx 560 - 590\text{m a.s.l.}$) where instability of surficial water flows and low gradient streambeds generated an unstable assortment of links among water bodies, swampy areas, and communicating channels, the whole



FIGURE 3. São José dos Campos plateau morphological map (Coltrinari, 2003, 2010).

constituting a *depression complex*, as in Santa Catarina river lower course (Coltrinari, 2005). The singular morphological arrangement is attributed to changes in water circulation due probably to superposition of Pindamonhangaba Formation conglomerates and sandstones over Tremembé Formation claystones and shales (Campanha, 1994) that probably shortened sub-surficial water circulation and favoured lateral progression of geochemical processes and development of larger depressions (Coltrinari, 2003).

In the NE sector isolated depressions occur in the upper section of *dambos* with dry flat bottoms. Traces of concentrated flow are frequent either in streambeds or isolated over slopes and interfluves where cols cut convex ridges or linked hilltops to slopes. They showed also evidences of concentrated flow from upslope to base slope or immediately above flow scars on slopes. Together with fissures and landslip scars, mass-wasting deposits suggested the participation of mass-movements in slope evolution in this area.

DISCUSSION

LANDSCAPE EVOLUTION

Former studies on landscape evolution in Taubaté basin (Coltrinari, 1975, 1983, 1987) followed existing models (Ab' Sáber, 1960; Bigarella et al., 1961; Bigarella et al., 1965a, b; Bigarella & Mousinho, 1965, and others) for paleogeographical reconstructions in the Brazilian tropics. Landscape evolution models adopted geomorphological and sedimentological data to identify and explain the origin of topographic levels - extensive, planation surfaces or pediplains, or restricted - pediments or *glacis*, identified in different compartments, as well as related unconsolidated coarse materials (*elluvium*) and slope sediments (*colluvium*).

The origin of those levels was attributed to mechanical/physical morphogenetic episodes under semi-arid environmental conditions concomitant with glacial periods in the North hemisphere alternating with development of soils, fluvial systems, and the vegetal cover that took place during humid periods, the interglacials. Consequently, present-day landforms would be reflections and consequences of alternate cold/dry/morphogenesis and hot/humid/pedogenesis periods related to Pleistocene glacial cycles (Penck & Brückner, 1909; Willman and Frye, 1970, apud Bowen, 1985).

Around 1990 results from soils research developed according to the structural analysis of the pedologic cover and reconsideration of morphogenetic processes nature and their interactions with landforms materials (Coltrinari, 1992) led to associate results from soil research as proxy evidences of former conditions of landscape evolution in the study area to this research. Relationships among landform topographic levels and soil types, as well as slope evolution by mass movements and soil profiles similar to present-day oxysoils (Coltrinari, 1992) were proposed suggesting that 1) stability of Quaternary climatic parameters favoured uninterrupted pedogenesis, and 2) the lack of geomorphological and/

or pedological evidences of humid/dry alternate climates invalidate former evolution models and allow the proposal the adoption of a new one.

THE ETCHPLANATION CONCEPT

The accumulation of weathered or pedogenic materials generates a special type of paleosurface evolving by rock corrosion by acid solutes – etch plains or etched plains (Wayland, 1933), or double-planation surfaces (Büdel, 1957). The name evoked relationships among rock corrosion by acids and artistic aquaforte engravings to describe the traces of acidic waters circulating within the weathered mantle in contact with the rock basement and modelling the subjacent surface under the regolith base (Coltrinari, 2003). For the first time in Brazil Novaes Pinto (1987) focused the relevance of differential physical-chemical weathering to explain the development of “chapadas” in Central Brazil. More recently Schaeffer & Dalrymple (1995) informed that in the high Rio Branco basin (Northern Amazonia) all the planation surfaces – previously associated to pediplanation processes – developed under etchplanation processes and denudation of previously weathered material since the Middle Tertiary.

Coltrinari & Filizola (1993) proposed the first revision of hypothesis about genesis and evolution of macrofeatures considered as remnants of a Neogene surface (Martonne, 1943/1944) in Taubaté basin based upon the occurrence of high continuous hilltops along the SW border of São José dos Campos plateau that progressively loss height and width towards NE, and detailed analysis of landforms and pedologic cover in São José dos Campos plateau. Further results (Filizola, 1993; Filizola & Boulet, 1993, 1996; Coltrinari, 1997, 1998, 1999) sustained efficiency of surficial and sub-surficial geochemical processes in landform genesis suggesting actions of etchplanation type processes in the development of São José dos Campos paleosurface.

CONCLUSIONS

- Regional extension of pseudo-karstic features demonstrate the significance of geochemical processes in São José dos Campos plateau landform evolution.
- Attributes of landforms – distribution, shape, and permanence – as depicted in aerial photographs reveal complex interactions among exogenetic processes and endogenetic influences in their origin and evolution.
- Progressive lowering of interfluvies from SW to NE and increasing number of pseudo-karstic features suggest the downgrading of a Neogene planation surface probably due to water table adjustment to a regional base-level associated to basement rock exposures. Dry depressions, evidences of amphitheatre-like head valleys, cols, and dry-shallow valleys demonstrate geochemical processes and surficial water circulation associated to ancient higher levels of the water table.
- Predominance of solution processes indicates that São José dos Campos plateau landscapes evolved under humid tropical environmental conditions at least during the Upper Cainozoic.
- The consideration of geochemical exports/material loss from the weathering front or basal weathering surface where etching progresses sustain the substitution of previous models and the adoption of etchplanation principles.
- In the other hand evolution of the upper (soils/landforms) paleosurface in São José dos Campos plateau does not seem to follow completely Büdel's (1957) model, i.e., the present-day surface is not submitted to processes related to surficial water circulation. Evidences (Filizola, 1993; Filizola & Boulet, 1996, and others) indicate that material loss occur within the whole pedologic cover and geochemical erosion provokes the increase of slopes gradient, linked to base level lowering in depressions and valleys. Those data seem to corroborate de Martonne's (1943/1944) hypothesis on slope evolution in the study area by solution of rocks minerals.

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