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Evolution and opening of closed depressions developed in a quartz-kaolinitic sedimentary substratum at Taubaté basin (São Paulo, Brazil), and analogy to the slope evolution

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Abstract

The occurrence of dated peat (17,000–12,500 yr B.P.) in the soil in a closed depression in quartz-kaolinitic rocks of the Taubaté basin, Brazil, allowed (1) reconstruction of the evolution of this depression, and (2) estimation of the rate of sinking. The analogy with the soil cover of a slope in the same area has shown that this valley developed by the same mechanisms as those of the depression. Chemical erosion is the main agent for the generation of landforms in this region.

1. Introduction

Closed depressions, basin forms that lack a stream outlet, are formed by loss of soluble material from the base. The best known forms are karstic sinks in limestone areas, but they are also encountered in other types of rocks. In Brazil, these depressions can be found in quartz-kaolinitic sedimentary rocks in Vale do Paraíba, where they are quite abundant, in the Paulinia region (SP), and in the Boa Vista region (RR). They also occur in migmatites, as in the Serra do Mar, Sorocaba do Sul region (SC) (Queiroz Neto, 1993). Furthermore, in Vale do Paraíba, our study area, several valley heads have an amphitheater shape very similar to thos of the closed depressions, suggesting that they were previously closed depressions. Therefore, the question is: have these depressions been captured by valleys or were they formed by another mechanism?

In Africa, closed depressions have been observed on the Continental Terminal ironcrust in Niger (Boulet, 1964; Busche and Erbe, 1987), in the southern part of Ivory Coast (also on the Continental Terminal, Humbel, 1964), on cratonic rocks in Madagascar (Soubies, 1974), on the Bateké arenites in Congo (Schwartz, 1988). In Uganda, these forms are common in metasedimentary rocks (Doornkamp, 1968; McFarlane, 1976). Other examples can be found on ultrabasic rocks in New Caledonia (Trescases, 1975), and on igneous rocks in Papua New Guinea (Löffler, 1978) (see also McFarlane and Twidale, 1987).

In Brazil, these closed depressions, although explained as forms of geochemical origin (Ruellan, 1943; Ab'Saber and Bernardes, 1958; Suguio, 1969; Coltrinari, 1975), have never been studied in detail. They are, however, very interesting natural models because they work as traps for sediments that migrate downslope. Development also appears to be largely attributable to export of material in solution.

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This study attempts to differentiate the chemical role from that of surface mechanical transport in the evolution of closed depressions and associated valleys.

2. Materials and methods

The Taubaté basin, where the studied depressions are located, is part of the Paraíba Graben whose

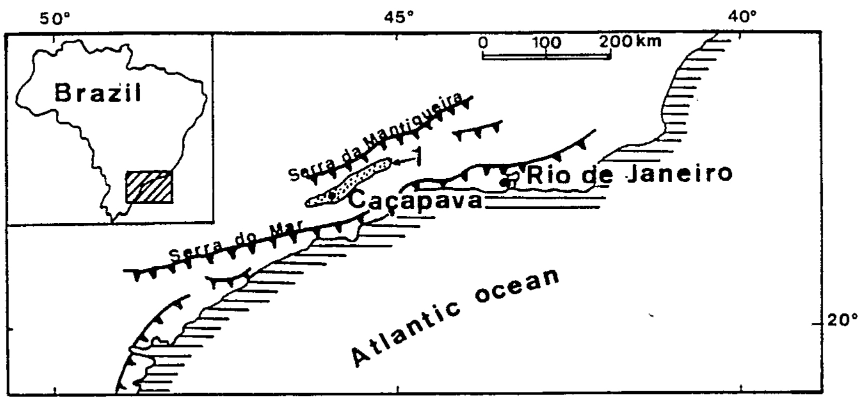

Fig. 1. Location map. 1. Taubaté basin.

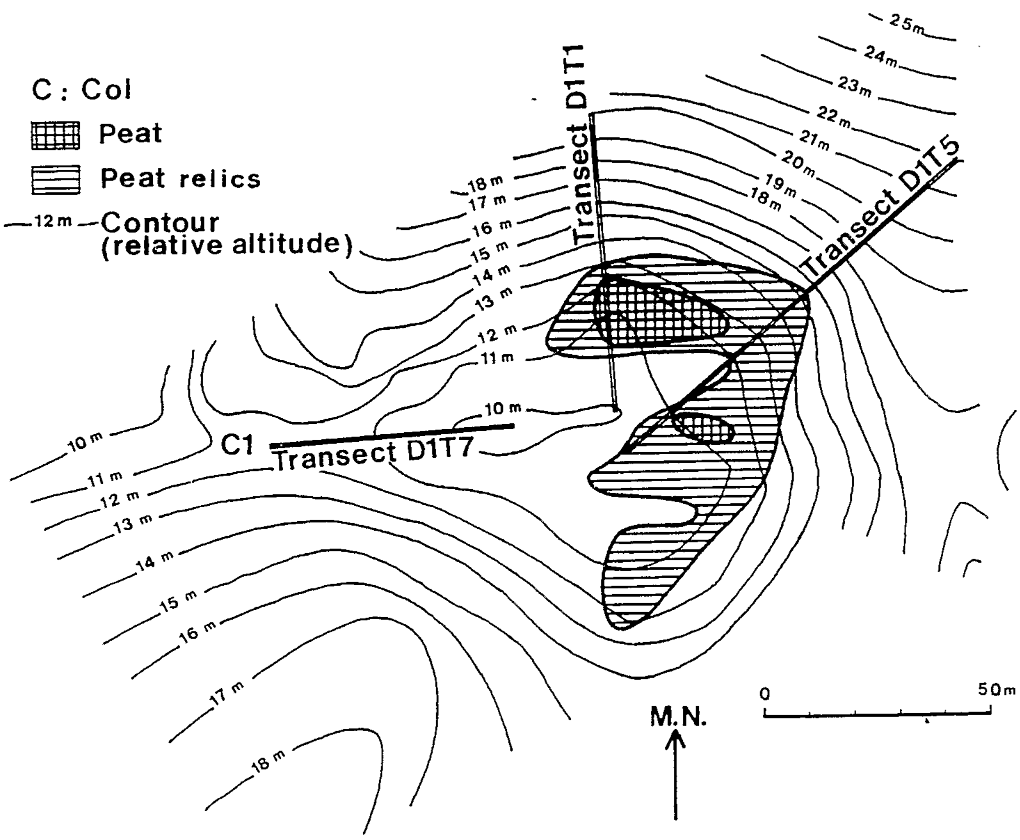

Fig. 2. Topography of D1 depression, location of transects and extension of peat and its relics.

origin is related to the evolution of the continental rift system that borders the Santos basin (Almeida, 1976). The sediments that fill this graben are of Tertiary and Quaternary age. The depressions are mostly recent rocks — the Pindamonhangaba Formation (Riccomini, 1989) — which are fluvial deposits made up mostly of fine quartz-kaolinitic sediments (mudrocks), interbedded with coarser layers (sands and pebble layers). Tectonic activity was intense during the Tertiary, becoming more quiescent during the Quaternary (Suguio and Vespucci, 1986; Riccomini, 1989).

The closed depressions are located on top of the hills or on interfluves. Those under study are located in the Caçapava area (Fig. 1). The local climate is humid tropical with rainfall ranging from 1000 to 1500 mm. Maximum annual temperatures range from 25°C to 30°C, and minimum temperatures from 5°C to 10°C. The soil cover in the depressions and the underlying weathered sedimentary rocks was studied by means of transects.

3. Soil cover configuration of a valley and a depression

3.1. The study of a closed depression: Depression D1

Depression D1 is located at an altitude of 607 m and has an almost flat bottom of elliptical shape (80 m × 100 m). The sideslopes surrounding it are concave–convex with maximum gradients of 16%. These slopes are broken by cols; the lowest one, C1

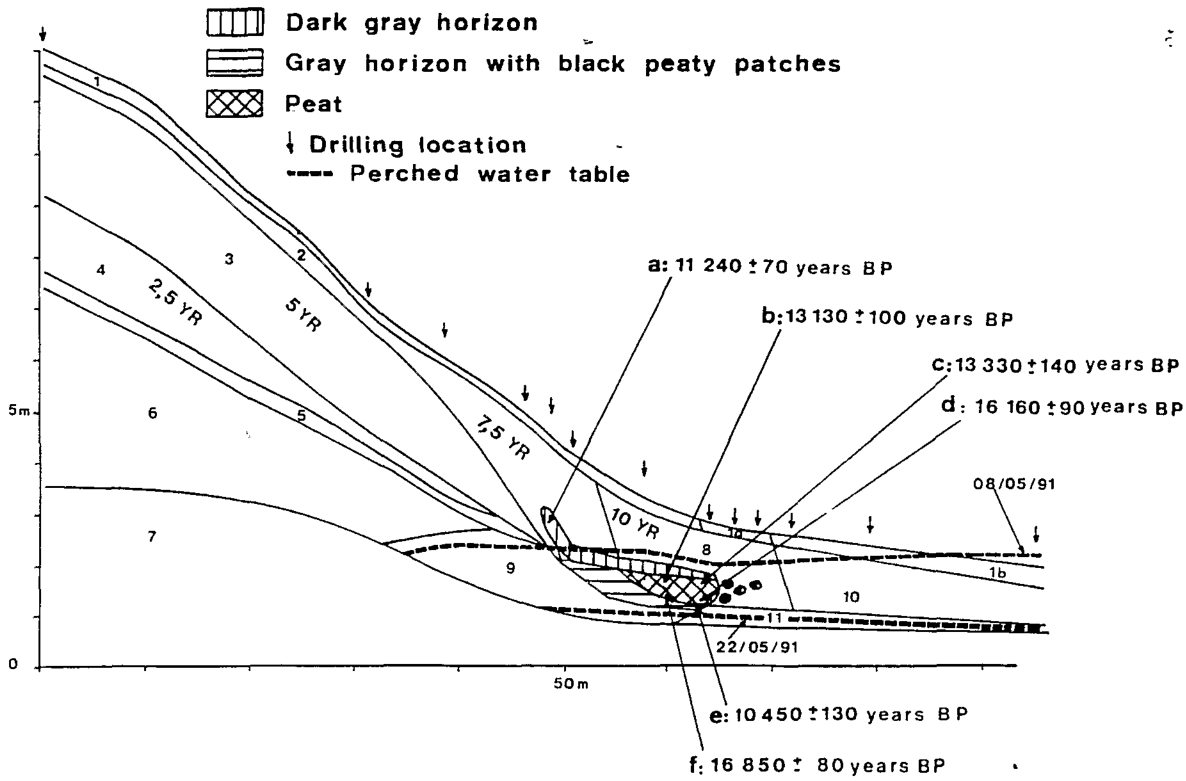

Fig. 3. D1T1 transect and location of data for radiocarbon analysis. 1. Humic dark brown sandy clay loam horizon, becoming black (1a) and subsequently with ochre spots (1b). 2. Strong brown sandy clay horizon. 3. Yellowish red sandy clay horizon. 4. Red sandy clay horizon. 5. Transition horizon between 4 and argillaceous rock. 6. Argillaceous rock with violet patches. 7. Green argillaceous rock. 8. Yellowish brown sandy clay horizon. 9. Yellow and red argillaceous rock. 10. Grayish brown sandy clay horizon with red spots. 11. Light gray sandy clay horizon with red spots.

(Fig. 2) is 1.7 m from the bottom of the depression. Sugar cane is grown on the slopes, and, seasonally, beans and corn on its bottom.

3.2. *Configuration of the soil cover and of the underlying sedimentary materials*

In the D1T1 transect (Figs. 2 and 3), the soil cover is thick upslope (4.5 m) and shows a sandy clay microaggregated oxisol, with yellowish brown upper horizons (1 and 2) and red lower horizons (3 and 4). It grades downwards into a white argillaceous rock (layer 6) with violet mottles, a centimetre in diameter, and occasional sandy layers. Deeper (8.50 m), a green argillaceous rock is encountered (layer 7), with a 1 m transition over which the violet mottles progressively disappear.

Cross-sections along road showed that this green argillaceous rock with gley morphology is part of the Pindamonhangaba Formation, and that it is not related to the current soil genesis. It is found at 1.5 m depth in the centre of the depression and at 8.5 m depth upslope.

Lateral soil cover variations mainly concern color. The soil color upslope is dominantly red (Fig. 3: horizons 3, 4) and progressively changes downslope into a yellowish brown color (10YR, horizons 2 and 8), whereas close to the bottom of the depression, some reddish brown spots exist followed by red ones. Downslope, a gray horizon (Fig. 3) is found at 1.4 m depth, within the well drained horizon, 7.5YR (2). It is 30 cm thick and is richer in organic matter than the surrounding horizons. It becomes darker and thicker at the bottom of the slope, with peaty patches. About 6m further downslope, fine black peat appears in the middle of this dark horizon. The peat in D1T1 extends laterally for about 10 m. The continuous peat layer ends abruptly at the margin of the base of the depression and only isolated patches, gradually less black and less numerous, occur over a distance of approximately 4m beyond that. The peat and the gray organic horizons, covered by mineral horizons 1 to 1.7 m thick, are found only in the eastern portion of the depression, being absent in the center of it. The gray horizon extends up to 3.9 m higher upslope in adjacent transect (D1T5), as shown in fig. 2.

Samples of the peat and the gray horizon and its extension upslope have been dated (Beta Analytic). These locations are shown in Fig. 3. The apparent ages of these peats are between 13,130 ± 100 yr B.P. and 16,850 ± 180 yr B.P. The gray materials are younger (10,450 ± 130 yr B.P. up to 11,240 ± 70 yr

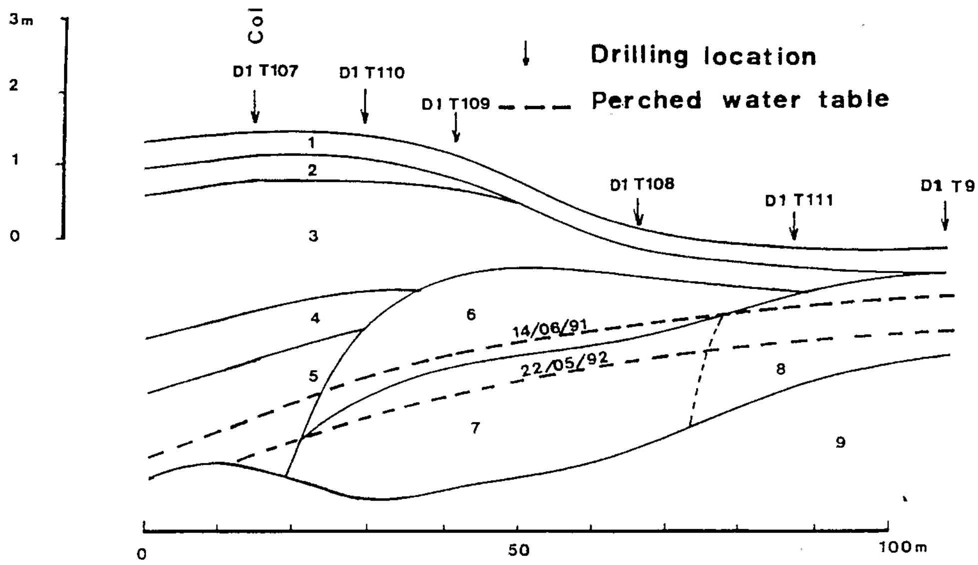

Fig. 4. D1T7 Transect. 1. Humic horizon. 2. Bright brown, sandy clay horizon with dark gray patches. 3. Reddish brown sandy clay horizon. 4. Yellow sandy clay horizon with red spots. 7. Light gray sandy clay horizon with brown network and ochre spots. 8. Grayish brown sandy clay horizon with red spots. 9. Green argillaceous rock.

B.P.). Dating of the outcropping peat in the central portion of another depression (Sony depression, Fig. 4) gave an age of 12,710 ± 150 yr B.P. (Filizola and Boulet, 1993).

3.3. Observations of the groundwater

On May 8, 1991, a day after a heavy rainfall (40 mm) that followed a dry period, a perched water table was observed in D1T1 transect (Fig. 3). This perched groundwater has a bevel shaped end at the margin of the depression and the deep drilling further upslope did not reach free water. That day, the depression was covered by a water layer of 20 cm. The slight reversal of slope of the water table probably indicates that, after a heavy rainfall, the depression floods because of runoff and then, surface water infiltrates into the slope. Fourteen days later, however, surface water had disappeared and the water table was 135 cm lower. The water table level then

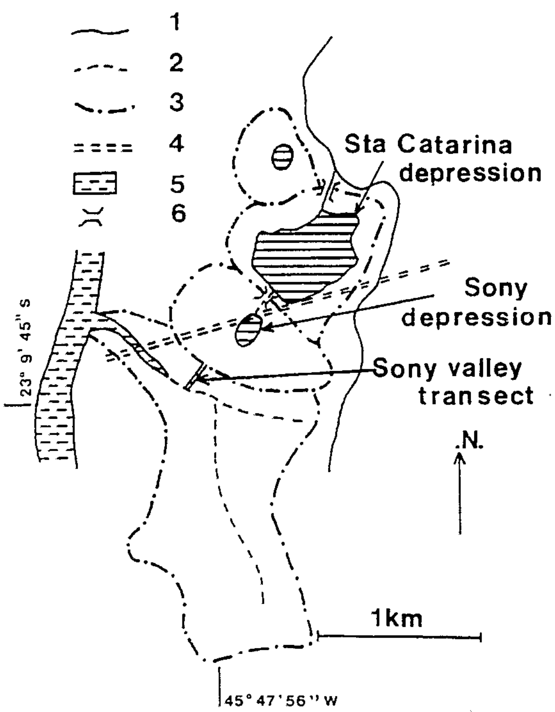

Fig. 5. Location map of Sony and Santa Catarina depressions and of Sony valley transect. 1. Well incised drainage axis. 2. Drainage axis with no important incision. 3. Watershed. 4. Highway. 5. Alluvial plain. 6. Col.

sloped towards the centre of the depression, which shows that after being recharged, this perched groundwater flows towards the depression where it drains away. The study of the D1T7 transect (Fig. 2 and 4) showed that the perched water table was lower in col C1 than in the center of the depression, a situation found only in this col.

At the summit of col C1 (Fig. 4) the soil consists of the following horizons: two upper horizons 70 cm thick, one dark-brown (horizon 1), the other bright brown (horizon 2). Overlying these are various horizons that show ferruginous differentiation becoming increasingly reddish brown with depth (horizon 3), then with red spots in brown material (horizon 4) and, at depth, red spots in yellow material (horizon 5). This indicates some iron mobilization and precipitation. The horizons are almost parallel to the topographic surface of the col.

Towards the bottom of the depression, a bevelling light gray horizon with brown networks and ochre spots appears in contact with the green argillaceous rock (layer 9). It is overlain by a light grayish brown horizon with red spots (horizon 6). This assemblage shows that hydromorphic conditions increase downwards. Downslope this hydromorphic horizons thickens and replaces the soil cover of the col.

The phreatic water table level was measured twice alongside this transect (Fig. 4); the first time a month after the above mentioned rainfall, on June 14, 1991; the second time during a dryer period, on May 22, 1992. On both occasions, the water table had a gradient of about 2%, opposite to the surface slope. This shows that the perched groundwater flows from the bottom of the depression towards the col C1. During the first measuring, in June 14, 1991, the water table was 15cm above the floor of the groundwater (horizon 9) in the col; thus, groundwater flow was out of the depression. During the second period of measuring (May 22, 1992), the top of the groundwater table ended on this floor, before reaching the col. The depression was dry. We assume that when the depression floods (which does not happen very often and was seen only once, on May 8, 1991), this perched groundwater level probably reaches the top of horizon 4 (Fig. 4). We also noticed that the top of the water table had a gradient similar to the top of the deep hydromorphic horizon (7).

On the other side of this col there is another depression that receives overflow waters from the D1 perched water-table. This other depression located NNW from D1 is drained by a small valley.

3.4. Study of a concave valley slope

The slope that was studied, near the Sony depression (Fig. 5), is in a dale-type valley, a shape typical of the valleys in this area. Its soil cover (Fig. 6), similar to that of depression D1, is, however, thicker (7 m versus 5 m in D1). The parent rock is a sandy clay sediment with coarse quartz skeleton. Downslope, buried peat 1.0–1.2 m thick underlies the mineral horizons. A gray organic horizon replaces it upslope but is absent at the drainage axis.

4. Discussion

4.1. Evolution of depression D1 as inferred from the geometry of the peat and the gray organic horizon

The continuity of the peat and the gray organic patches buried in the slope shows that they belong to the same original peaty formation. We can deduce, by analogy with the present peatbogs, that this material was originally horizontal. This peat, now located inside the slope soil cover, gradually disappears by mineralization. Curiously, it also disappears in the depression, being absent in the center and eastern half of it (Fig. 2). The study of other depressions (Sony and Santa Catarina, Fig. 4), whose bottoms are always water-saturated or flooded, showed that under these conditions the peat remains on the depression bottom. When the lateral drainage starts (towards the col C1, in D1), the peat is destroyed. Thus, peat disappearance from the central portion of D1 would be favored by rapid drainage.

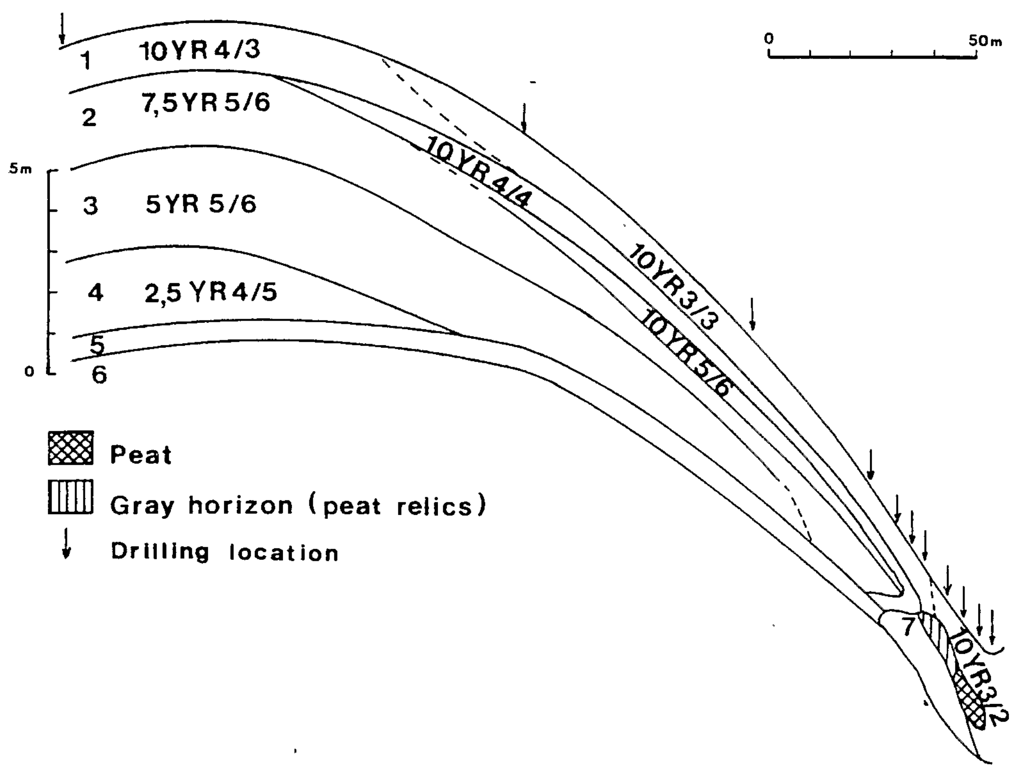

Fig. 6. Sony valley transect. 1. Humic dark brown sandy clay loam horizon. 2. Strong brown sandy clay horizon. 3. Yellowish red sandy clay horizon. 4. Red sandy clay horizon. 5. Reddish brown sandy clay horizon with pink compact volumes. 6. Pink sandy clay material. 7. White sandy clay horizon with red spots.

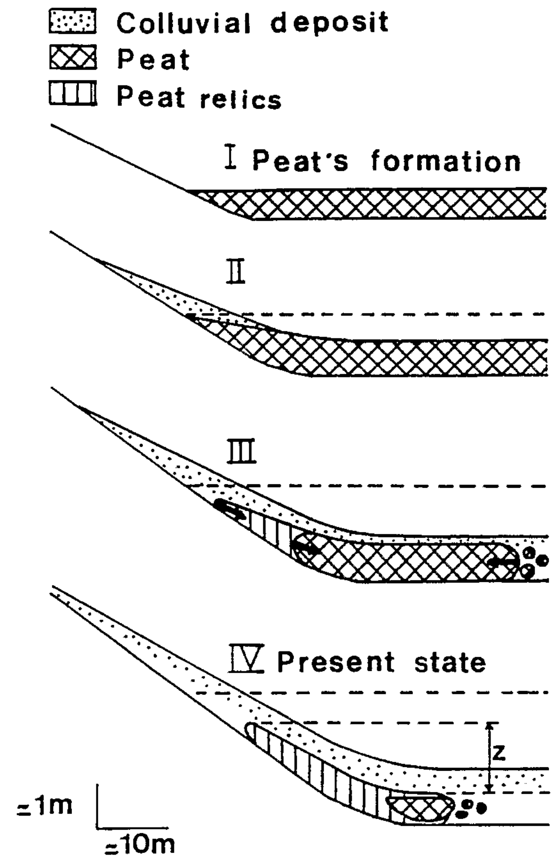

Fig. 7. Evolution of D1 depression since peat formation. Z: estimated sinking of the depression since peat formation (underestimate).

On the basis of the present state of depression D1, reconstruction of probable evolution is possible since the time of peat deposition (Fig. 7). In stage I the depression bottom was wider than now, reaching the present upslope limits of peat relics (D1T5 transect, Fig. 2). This is the lowest limit because degradation of peat is progressive. It may have had a greater extension but those remains have disappeared. Then, the depression sinks and shrinks gradually (stages II–IV). Because the lowering of the base level, colluvial deposits gradually cover the peat. Another interpretation would be to concede that the peat originally formed on the slope. A water outlet would be required on the slope, however, which is inconsistent with hydric dynamics of the Oxisol cover. Furthermore, peat relics upslope currently found in a well drained horizon, implies that the Oxisol cover would have mineralized it.

According to the dating results, the peat began to form at approximately 17,000 years B.P. It is possible to appraise the average rate of speed of sinking of the depression on the basis of the oldest date and on difference in altitude between the highest ric of the peat and the depression bottom (3.9 m). An average rate of sinking is 0.23 mm per year (Filizola and Boulet, 1993), or 23 m in 100,000 years. This rate is higher than the usually measured weathering rates, which vary from 0.5–2.5 m/100,000 yr depending on parent rock and climate (for a review see Nahon, 1991 and Tardy, 1993). Export of matter in solution, however, is more important from the lower slopes than from the upper parts where water is lost by lateral runoff, whereas the lower slopes are overfed by rain water that flows and infiltrates, and by oblique drainage. The average sinking rate that we calculated allows the evaluation of the role of chemical erosion in increasing slope gradients, but not the average rate of lowering the weathering front.

The youngest ages obtained from the transformation of the peat horizons can be attributed to recent carbon introduction during its mineralization. The age of sample "e" (Fig. 3), located below sample "d", presents an apparent age 6000 years younger which demonstrates this rejuvenation.

The importance of colluvial processes since the beginning of peat formation can also be assessed because the colluvium overlying the peat came from upslope. The maximum thickness of colluvium is 1.5 m in depression D1. The colluvial deposit compensates the geochemical sinking and tends to fill the depression. The balance between both mechanisms shows that chemical erosion is more efficient than colluvial processes, as shown by the existence of the depression.

The isochromatic contour line (Fig. 3) that limits the bright brown materials (7.5YR) from the yellowish ones (10YR) cuts the colluvial deposits. Thus, pedogenesis in the colluvial material rapidly causes toposequencial differentiation. In the absence of a stratigraphic reference, like peat, it becomes difficult to distinguish colluvial material from in situ material.

4.2. Probable mechanisms for the opening of closed

depressions

As seen, D1 is a closed depression. The piezometric study, however, showed that, after heavy rainfalls, lateral flow of its perched groundwater through col C1 favors quick drainage of D1. This promotes the lowering of the col by export in solution. Thus, it seems that lateral flow of internal water through the lower col will finally lower the col and open the depression. Closed depressions somehow create an outlet; valleys did not capture these depressions.

4.3. Origins of closed depressions

Karstic-type forms are not restricted to regions of calcareous substratum but can also appear in regions of less soluble substratum (see Introduction), as in Vale do Paraiba. The development of closed depressions is obviously favored by vertical loss of water through the underlying less permeable sediments (argillaceous rock). A map of these depressions (Fig. 8) shows that they are located in accordance with well marked lineaments, the clearest ones being N70 and N280. This is the case of the very dense series of depressions in which depression D1 is located. These lineaments must be deduced to be fault systems.

The study of a road cut (Carvalho Pinto Highway) that crosses an interfluve which shows a fault, reveals that the 20 m wide tectonic breccia bordering the faults favors deep water infiltration, whereas the adjacent intact clayey layers retard it (Filizola, 1993). Nevertheless, this does not in itself explain the development of the closed depressions because it is normal for drainage to follow faults. These depressions apparently are formed at fault intersections, where brecciation is more intense and local deep infiltration occurs. This hypothesis is supported by the occurrence of depressions where lineament intersection is evident.

4.4. Evolution of the slopes of the dale-type valleys (Fig. 9)

The analogy of the soil cover of the slope that has been studied with those of the depressions and the presence of peats that extend upslope suggest an evolution similar to the one shown in Fig. 7. During the formation of the peat, the bottom of the valley

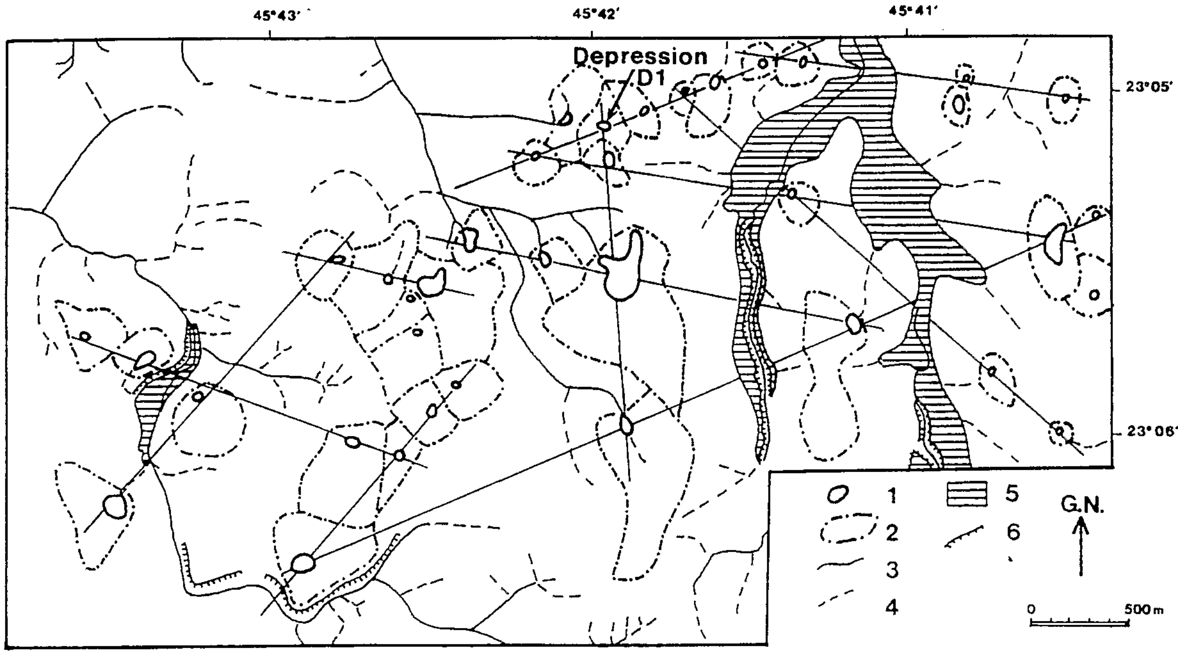

Fig. 8. Map of the depression distribution of D1 area. 1. Depression bottom. 2. Limit of the depression watersheds. 3. Well incised drainage axis. 4. Drainage axis with no important incision. 5. Alluvial plain. 6. Incision.

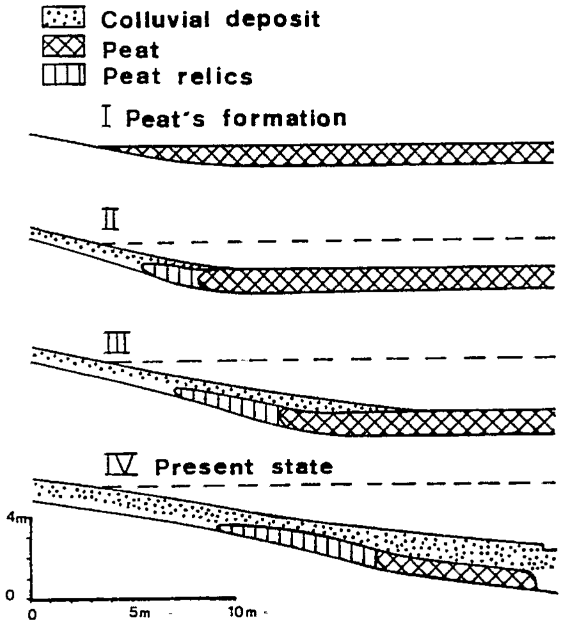

Fig. 9. Sony valley slope evolution since peat formation.

was flat and swampy, favoring the development of abundant vegetation and organic matter accumulation. Then, this small alluvial plain begins to sink and to shrink with no important incision because no erosion was observed in the peat. This sinking, followed by colluvial processes, cover the peat, first at its border and then all over its extension. Now, the drainage axis, here a slightly marked bed (15 cm) shows flow only during periods of rainfall and it is fed by the outcropping water table, a hundred meters upstream. As in D1, the mineral horizons overlying the peat are attributed to the colluvial deposit. They are slightly thinner (1.2 m) than the ones found in the depressions which vary from 1.5–1.7 m. An explanation may be the export of a small amount of colluvial materials along the drainage axis. Thus, the sinking of the dale-type valleys in this area is also largely the result of chemical erosion which increases slopes, whereas colluvial processes tend to reduce them; the balance clearly favors chemical erosion.

5. Conclusions

The results found show that the chemical erosion in a landform on quartz-kaolinitic sediments in a humid tropical environment occurs rapidly. Closed depressions are excellent natural models because they are sumps for solid materials. Our model assessed the rate of sinking of a depression because of the presence of datable ancient peat. This adressed the role of chemical erosion in slope increase but not the average rate of lowering the weathering front.

Piezometric measures showed that the perched groundwater confined inside the closed depression flows internally through the lower col. Thus, the opening of the depressions and the formation of an outlet result from the internal dynamics of these depressions rather than from capture.

Tectonics initiate these depressions because they are located at fault intersections where water infiltrates deeply in to brecciated rocks, whereas the undisturbed adjacent clayey layers decrease infiltration. The abundance of closed depressions and valley heads in amphitheater shape at Vale do Paraiba could then be explained by the differential leaching of an area affected by intense tectonic activity (Riccomini, 1989).

Finally, observations permit extrapolation to explain the evolution of the depressions into the slopes of this region and the dale-type valley slopes quite typical in this area. The evolution of the landforms of Taubaté basin is mainly a function of chemical erosion.

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