ELSEVIER

Catena 49 (2002) 129–137

CATENA

www.elsevier.com/locate/catena

The porosity of tropical soils and implications for geomorphological and pedogenetic processes and the movement of solutions within the weathering cover

Heinz Sander*

Geographisches Institut, Universität zu Köln, Albertus-Magnus-Platz, D-50923 Cologne, Germany

Received 10 July 2000; accepted 10 November 2000

Abstract

As there is a lack of research carried into the relationship between soil porosity, pedogenesis and geomorphological processes, this study contains an overview of research results on this topic from the 'soil and relief in the tropics' project at the University of Cologne. The macroporosity (volume, poretypes, porefillings, etc.) of 641 tropical soil samples was examined using thin sections. The samples form part of a database project, which allows correlation of field and laboratory parameters. Analyses show a high macropore content even in fine-grained soils and subsoil and saprolite horizons. Pore fillings are mainly found in relic soils on old landscapes, yet the complete filling of pores seems to be the exception. Thus, the passage of solutions and suspensions within a soil cover has, in most cases, only minor restrictions. This suggests that the lateral transport of solutions, which may be crucial for the nutrient supply in areas with depleted soils, may be possible in tropical regions. Pore fillings may also be used to reconstruct polygenetic soil development. They allow a relative dating of soil-forming processes either by establishing a 'pore stratigraphy' or by identifying precipitates that are incompatible with each other in the same horizon. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Geomorphology; Micromorphology; Pedology; Polygenetic soils; Porosity; Thin section analysis

1. Introduction

The relationships between soil porosity and geomorphology are fourfold.

- Pores permit the subcutaneous vertical and lateral movement of solutions and suspensions.

---

* Fax: +49-221-470-4917.

E-mail address: heinz.sander@uni-koeln.de (H. Sander).

0341-8162/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.

PII: S0341-8162(02)00021-8

- Pore size distributions influence soil water and soil air balances, and are thus a major factor in creating the milieu for weathering processes.
- By influencing the infiltration of water and permeability, pores are a factor in controlling erosion and mass movement processes.
- Analyses of pore fillings can serve as a tool for the reconstruction of the polygenetic development of weathering covers. Thus, they reveal information about the age of the soil and the geomorphic stability of land surfaces.

Despite these facts, it seems that little systematic research on the relationships between soil porosity and geomorphological processes has been carried out. This applies especially to pore size distributions, although pores differ significantly in their influence on geomorphic processes according to their size. This study focuses on macropores, i.e. pores with a diameter > 10 μm. This pore size allows the ready movement of water and is thus of great importance for the vertical leaching of soils, lateral transport and precipitation processes.

2. Methods

Research was carried out as part of the 'soil and relief in the tropics' project (1990–1995) at the Geographical Institute of the University of Cologne. A team of four researchers (Bremer, Laufenberg, Sander, Kreutzwald and partly assisted by Schnütgen) analysed some 1300 samples of soils, sediments, duricrusts, stones and weathering rinds. Preliminary results have been published in Bremer (1992, 1995), Laufenberg (1992, 1995a,b, 1999), Sander (1992, 1995a,b, 1996) and Kreutzwald (1992).

After omitting samples of fresh rock, duricrusts, dunes, river sands, dune sands and gravel, 641 soil samples were analysed with regard to soil porosity (Sander, 1995a). The material represents a broad spectrum of parent materials, climatic conditions, soil horizons and relief positions. Samples were collected by Prof. Bremer and collaborators (Späth, Schnütgen and Kreutzwald) in Australia (Queensland, Northern Territory), Central (Costa Rica) and South America (shield areas of Guayana and Brazil, lowlands of the Amazon Basin), India (Westghats, Dekkan) and Africa (Mali, Kenya).

Analyses centred on the interpretation of thin sections, thus all information refers to the microfabric of soils and to macropores. After estimation of pore volumes, the most frequent types of pores (e.g. cracks and wedges), the amount and the kind of fillings and the microfabric of each sample were determined. In contrast to other possible definitions, the term 'pore filling' was applied even if the pores were only partly filled or if only traces of fillings were detected in the pores. The volume of the porespace actually filled was also

Table 1
Percent of samples containing specified volumes of macropores

	Volume of macropores (%)						
	0	5	10	20	30	40	50
Percentage of samples ($n = 641$)	3	10	32	34	16	3	1

Table 2
Porosity and pore size distribution of mineral (C-content <2%) and organic soils according to Scheffer and Schachtschabel (1998: 145)

Soil	Porosity (%)	Macropores (>10 μm) (%)	Mesopores (10–0.2 μm) (%)	Micropores (<0.2 μm) (%)
Sand	46±10	30±10	7±5	5±3
Silt	47±9	15±10	15±7	15±5
Clay	50±15	8±5	10±5	35±10
Peaty soil	70±10	5±3	40±10	25±10
Fen	85±10	25±10	40±10	25±10

noted. The database contains many other field and laboratory parameters (e.g. granulometrical and mineralogical analyses) besides porosity. This allows a large number of correlations to be made between the different factors. For the complete data sheet, see Bremer (1992); analytical methods have been described in detail by Schnütgen (1981), Laufenberg (1995b) and Sander (1995b); the data set is identical with the one described in Sander (1995a).

3. Results of thin section analyses

3.1. Soil porosity

3.1.1. Soil porosity and soil microfabric

The content of macropores is high: more than half of the samples contain 20% or even more pores and another third has about 10% macropores (Table 1). Therefore, only few restrictions on vertical and lateral water movements exist.

Table 3
Percent of samples with a defined texture containing a specified volume of macropores

Samples	Volume of macropores (%)			n
	≤10	20	≥30	
All samples	45	34	20	641
Sand content 0–20%	45	41	15	129
Sand content 21–40%	44	35	21	118
Sand content 41–60%	51	26	23	110
Sand content 61–80%	49	23	29	85
Silt content 0–20%	41	31	25	117
Silt content 21–40%	42	36	21	216
Silt content 41–60%	50	32	17	130
Clay content 0–20%	49	29	23	199
Clay content 21–40%	48	33	20	176
Clay content 41–60%	36	41	23	89

Table 4
Volume of macropores in different soil horizons (percentage of samples)

Vertical position	Volume of macropores (%)			n
	0–10	20	30–50	
Topsoil	42	32	27	146
Subsoil	49	32	18	146
Saprolite	61	31	7	41
Topsoil, relic	33	37	30	30
Subsoil, relic	43	44	13	99

3.1.2. Soil texture and porosity

For extratropical regions, a close correlation between texture and porosity is assumed. The formula in Renger (1971) and AG Boden (1994) determines the porosity distribution in soils by computing factors for clay and silt content, content of organic substances and density. In addition, the diagrams in Kuntze et al. (1994, Figs. 84, 87 and 89) and Table 5.1–5 in Scheffer and Schachtschabel (1998: 145) show a close correlation between texture and pore size distribution (Table 2).

In the present sample, the influence of soil texture on porosity was smaller than expected from these published assumptions (Table 3) as different pore types have their maximum occurrence in soils with different textures. Primary pores may occur in sand-rich samples, irregular wedges between soil aggregates are often found in loamy soils, whereas cracks and biogenous pores are mainly observed in materials rich in clay and silt.

3.1.3. Soil horizons and porosity

Cross tabulation of position in the profile versus porosity reveals two insights (Table 4).

- As expected, macroporosity decreases from the topsoil to the subsoil and the saprolite. However, even in subsoil and saprolite, macroporosity is remarkably high. This pattern of occurrence explains the rapid drainage of soils after rainfall and frequently high infiltration capacities.
- When soil horizons with relic features were compared with those without such features, the relic horizons are seen to have remarkably few samples with low porosity. This may point to the high stability of the soil fabric and the consequent preservation of pores.

Table 5
Occurrence of pore filling in different soil horizons and substrata (percentage of samples)

Vertical position	Samples with pore filling (%)	n
Topsoil	51	146
Subsoil	66	154
Saprolite	70	35
Topsoil, relic	70	30
Subsoil, relic	73	98
Sediment of reworked soils	35	66
Accumulation	50	46

Table 6
Degree of pore filling in samples with clay coatings (total number of analyzed samples: 641)

Samples	Degree of pore filling				n
	Trace	Margin	Half-filled	Completely filled	
Single clay coatings	46	25	21	5	177
Multiple clay coatings	19	25	47	9	32

This assumed stability of soil fabric may be confirmed by the distribution of pore fillings, which are more common in relic horizons than in soils without these features (Table 5). Table 5 also reveals two other features.

- The amount of pore fillings increases with depth. This is only partly due to the vertical movement of material. Lateral movement within the catena may also lead to the filling of pores, as has been shown, for example, in the formation of duricrusts (summarized in Bremer, 1995). Besides these considerations, pore fillings will be destroyed more easily near the surface where bioturbation and swell–shrink movements occur more often.
- Young substrata such as sediments of reworked soils and other accumulations show less pore filling than soils or even soils with relic features. This demonstrates possible relationships between the age of the soil and the occurrence of pore fillings.

3.1.4. *Clay coatings*

Clay coatings occur mainly in zones with marked wet and dry seasons. About 209 of the 641 samples showed signs of clay coatings on pore walls. However, these figures give a rather incomplete picture because in many cases, only very limited coatings were detected (Table 6). Even in those samples where multiple phases of formation of clay coatings have been detected, a complete filling of pores is rare (Laufenberg, 1995a).

The most important consequence of this observation is that in most cases, the development of clay coatings does not significantly diminish macropore volume (Table 7) (Laufenberg, 1995a). This is especially true in the case of single clay coatings, and the development of clay coatings appears to have only a very slight influence on the mobility of water in the soil.

3.1.5. *Relief position*

As pore fillings may be used as a rough indication of soil age, cross tabulations between the intensity of pore filling versus relief position were calculated to determine where old soils occur and if a correlation between age of the relief and age of the soil occurs (Table 8).

Table 7
Percentage of samples containing specified volumes of macropores: comparison of samples containing clay coatings with the entire sample set

Samples	Volume of macropores (%)							n
	0	5	10	20	30	40	50	
All samples	3	10	32	34	16	3	1	641
Single clay coatings	6	8	31	39	15	1	1	177
Multiple clay coatings	–	6	44	34	13	–	–	32

Table 8
Degree of pore fillings in soils of different relief positions

Relief position	Degree of pore filling			n
	>Trace	Trace	Empty	
Top of escarpment	46	40	14	35
Older plain	41	19	40	121
Younger plain	31	34	35	53
Partial etch-planation	27	33	40	96
Terrace	28	21	51	90
Upper slope	36	30	34	60
Lower slope	30	14	56	43
Footslope	49	22	29	45
Floodplain	26	21	53	38

The highest percentages of filled pores were found near escarpments, on foot slopes, old plains and upper slopes. Whereas the extensive pore fillings on foot slopes may in part be due to lateral transport of solutions, the concentration of pore filling on upper slopes supports field observations of high slope stability (Bremer, 1995). Soils with the least-filled pores were found at young relief sites such as terraces, floodplains and landforms, where etch-planation is restricted.

3.2. Lateral mobility of solutions and nutrients

A consequence of high porosity is the importance of interflow processes in tropical soils which Nortcliff and Thornes (1978) concluded from the reaction of small creeks after rainfall events. These authors developed the ‘cup’ model, which states that higher nutrient contents in the lower part of the weathering profile contrast with lower nutrient contents in the upper part. Combined with the assumption of strong interflow processes, this model allows an additional nutrient supply by lateral transport processes. This is exemplified by a detailed case study from the upper Rio Negro region of Brazil (Schnütgen and Bremer, 1985; Bremer, 1989). This region near the Casiquiare-bifurcation has a low internal relief of 10–20 m. Although annual precipitation is more than 3000 mm, only parts of the region are covered by forest, which grows mainly on loamy ultisols on granite. Analyses revealed that weatherable minerals may occur at a depth of about 2 m. On oval patches occupying some hectares each, a low vegetation cover occurs on a layer of pure white quartz sands (1–1.2 m thick), which cover a kaolinitic white clay. Analyses of the heavy minerals (Schnütgen and Bremer, 1985) reveal the white sand to be a completely depleted autochthonous weathering residuum of the granite. Along creeks, Amazonian Caatinga woodland grows on leached white sands.

Thus, the vegetation pattern may be explained by analysis of relief, the intensity of leaching of the soils and the lateral transport of nutrients through the pores. The completely leached white sands only allow the growth of low vegetation, whereas on the ultisols, forests occur. Near the creeks, a lateral supply of nutrients allows the existence of woodlands even on leached sands.

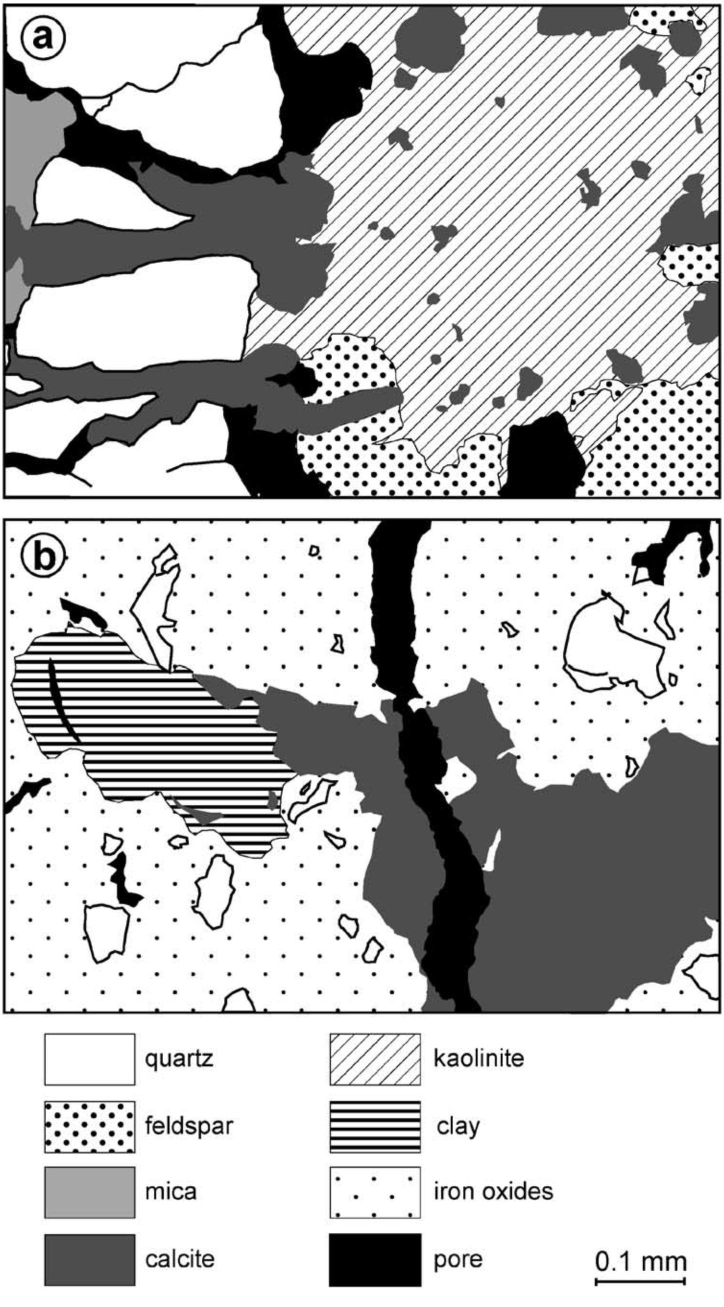

Fig. 1. (a) Thin section of weathered granite with an infiltration of calcite. (b) Thin section of ferricrete with a filling of pores by clay coating and calcite crystals.

3.3. Analyses of pore fillings as tool for the identification of polygenetic soils

Pore fillings hint at the polygenetic development of soil horizons in three cases.

- Fillings of different materials in one pore may reveal a ‘pore stratigraphy’ that shows a sequence of changing weathering conditions, e.g. a crystallization of goethite on the walls of the pores followed by the crystallization of carbonates may be a sign of aridification.
- Pores crossing each other may have different kinds of fillings that also indicate a ‘pore stratigraphy’.
- Pore fillings may not be compatible to the neoformation of the surrounding matrix.

This evidence of polygenetic soil development can easily be identified in soils as long as it has not been destroyed by excessive swell–shrink processes or strong bioturbation.

A case of incompatibility between pore filling and surrounding matrix can be observed 8 km west of Chillago, Queensland (Fig. 1a). The thin section shows in situ weathered granite. Quartz and feldspar grains are cracked; parts of the feldspar minerals have been altered to a clayey matrix with booklets of kaolinite crystals. In the cracks between the quartz grains, calcite has crystallized. It is unlikely that pore fillings (calcite) and matrix minerals (kaolinite) have developed under identical conditions. One possibility is that weathering of feldspar minerals and crystallization of kaolinite were associated with a wet phase followed by crystallization of calcite in voids during a drier phase.

In some cases, pore stratigraphy and incompatibility of pore fillings and matrix can be seen in the same thin section. Fig. 1b shows a ferricrete developed in a weathered metamorphite near a location called ‘The Garden’ in Central Australia. A large pore has been filled first by a clay coating and later by calcite. Thus, the sequence of lateritization–lessivation–calcite crystallization reveals an increasingly drier soil climate.

Soil features, which have developed under wet conditions, tend to be preserved in case of an aridification. If climate gets more humid, features of arid times may easily be destroyed within a short timespan. Thus, analyses of pore fillings, in most cases, reveal evidence of moister paleoclimatic conditions.

4. Conclusions

Tropical soils are characterized by a large volume of stable pores. Thus, water can infiltrate and solutions (with nutrients) can circulate easily even in soils with a fine-grained matrix. The rapid infiltration of large amounts of water may protect soils from surficial erosion but may increase interflow processes. The degree of pore fillings can be used as an indicator of the stability of soil and relief. In most cases, pore fillings have only minimal effects on the volume of macropores; this is valid especially for clay coatings.

Analyses of pore fillings with respect to pore stratigraphy or compatibility of filling and matrix may indicate a change in the soil water balance and the conditions for weathering and translocation processes. The occurrence of such polygenetic soils is a strong argument for the assumption of a high stability of the land surface. It has to be stressed that indicators of moist conditions are far more easily preserved than indicators of dry conditions.

Acknowledgements

The author thanks Prof. Dr. H. Bremer for inspiring discussions and information, especially on the lateral movement of solutions and nutrients. As part of the 'soil and relief in the tropics' project, this work was supported by the German Research Council (DFG).

References

AG Boden, 1994. Bodenkundliche Kartieranleitung. Hannover.

Bremer, H., 1989. Das natürliche Potential im westlichen Amazonasgebiet und im südlichen Venezuela. In: Hartmann, G. (Ed.), Amazonien im Umbruch. Aktuelle Probleme und deutsche Forschungen im größten Regenwaldgebiet der Erde, Reimer, Berlin, pp. 43–55.

Bremer, H., 1992. Relief and soil in the tropics—a data base. Z. Geomorphol., Suppl. 91, 1–10.

Bremer, H., 1995. Boden und Relief in den Tropen: Grundvorstellungen und Datenbank, Borntraeger, Berlin.

Kreutzwald, L., 1992. The comparison from soil samples of tectonically active and stable areas with examples from Central and South America. Z. Geomorphol., Suppl. 91, 29–34.

Kuntze, H., Roeschmann, G., Schwerdtfeger, G., 1994. Bodenkunde Ulmer, Stuttgart.

Laufenberg, M., 1992. The different types of weathering of tropical soils in relation to source-rock material—examples from southern and western India. Z. Geomorphol., Suppl. 91, 23–27.

Laufenberg, M., 1995a. Tongehalte und Toncutanen in tropischen Böden. Regensbg. Geogr. Schr. 25, 65–74.

Laufenberg, M., 1995b. "Korngröße", "pH-Wert", "Quarzkornanalyse", "Verwitterungsgrad". In: Bremer, H. (Ed.), Boden und Relief in den Tropen: Grundvorstellungen und Datenbank. Borntraeger, Berlin, pp. 227–230, 239–240, 265–273, 273–277.

Laufenberg, M., 1999. Tropische Verwitterung und Bodenbildung in basaltischen und kristallinen Gesteinen Indiens. PhD Thesis, University of Cologne.

Nortcliff, S., Thornes, J.B., 1978. Water and cation movement in a tropical rainforest environment: I. Objectives, experimental design and preliminary results. Acta Amazonica 8, 245–258.

Renger, M., 1971. Die Ermittlung der Porengrößenverteilung aus der Körnung, dem Gehalt an organischer Substanz und der Lagerungsdichte. Z. Pflanzenernaehr., Dueng., Bodenkd. 130, 53–67.

Sander, H., 1992. Polygenetic soils of Australia and their typical pedofeatures. Z. Geomorphol., Suppl. 91, 35–41.

Sander, H., 1995a. Untersuchungen zur Porosität tropischer Böden mittels dünnschliffmikroskopischer Erfassung von Grobporen. Regensbg. Geogr. Schr. 25, 143–155.

Sander, H., 1995b. "Röntgendiffraktometeranalysen", "Schwerminerale", "Farbbestimmung", "Dünnschliffanalysen". In: Bremer, H. (Ed.), Boden und Relief in den Tropen: Grundvorstellungen und Datenbank. Borntraeger, Berlin, pp. 231–236, 236–239, 241–244, 244–265.

Sander, H., 1996. Boden und Relief in Nordost-und Zentralaustralien. Verwitterungsintensität und Mehrphasigkeit in Abhängigkeit vom Niederschlag. Borntraeger, Berlin.

Scheffer, F., Schachtschabel, P., 1998. Lehrbuch der Bodenkunde. Encke, Stuttgart.

Schnütgen, A., 1981. Analysen zur Verwitterung und Bodenbildung in den Tropen an Proben von Sri Lanka. In: Bremer, H., Schnütgen, A., Späth, H. (Eds.), Zur Morphogenese in den feuchten Tropen. Verwitterung und Bodenbildung am Beispiel von Sri Lanka. Borntraeger, Berlin, pp. 239–275.

Schnütgen, A., Bremer, H., 1985. Die Entstehung von Decksanden im oberen Rio Negro-Gebiet. Z. Geomorphol., Suppl. 56, 55–67.