SOIL GENESIS AND LANDSCAPE EVOLUTION ALONG A TOPOSEQUENCE OF RIO ARAGUARI, CENTRAL BRAZIL

Henry Neufeldt
Institute for Soil Science and Soil Geography,
University of Bayreuth

Marilena Oliveira Griesinger
Department of Geography, Federal University of Uberlândia

Wolfgang Zech
Institute for Soil Science and Soil Geography,
University of Bayreuth

ABSTRACT: *Along a toposequence of Rio Araguari ranging from the Tertiary tableland to the valley floor, several soil profiles covering the main geological units are described. The soils were analysed chemically, microscopically, and by x-ray diffraction to elucidate soil genesis and landscape evolution. In addition, a fossil charcoal layer in an Oxisol nearby, located on the Tertiary erosion surface, was radiocarbon dated. Landscape development in Central Brazil is characterised by cyclic river incision and subsequent lateral erosion. As Oxisol formation below a fossil stoneline indicates advanced weathering under humid tropical conditions that are substituted by a semi-arid to arid climate, the cycles of incision and planation are predominantly caused by changing climatic conditions and not by epirogenesis, at least since mid Pleistocene. Results further indicate advanced soil weathering also of the youngest soils developed in the valley floor during the Holocene. The presence of a buried charcoal layer in a Tertiary Oxisol is an indicator of frequent burning. Radiocarbon age of the fossil charcoal is 4730 ± 70 BP. Results of others working in Brazil suggest that increased fires at deposition time be due to a drier period than before and afterward. Sedimentation on top of the fossil charcoal layer indicates strong redistribution processes on the nearly flat tableland and thus greater soil dynamics than generally assumed.*

Key words: soil weathering; landform evolution; paleoclimate; Central Brazil

RESUMO: *Ao longo de uma topossequência com início no alto do plateau terciário ao fundo do vale do rio Araguari, foram descritos e analisados vários perfis de solo correspondentes às principais unidades geológicas. Os solos foram analisados em seus elementos químicos, na escala microscópica e por difração de raio–x, com o objetivo de se buscar informações sobre a evolução da paisagem e a gênese dos solos. Uma linha de carvão fóssil encontrada no latossolo, na superfície de erosão terciária, foi datada por radio-carbono. O desenvolvimento da paisagem no Brasil Central tem sido caracterizado pôr uma sequência cíclica de incisões dos canais fluviais seguidas por fases de alargamento dos vales por erosão lateral. A formação de latossolo abaixo de uma linha de seixos fóssil parece indicar um periodo de intemperismo sob condições tropicais de umidade, seguido por um clima semi-árido a* *árido. Assim, o aprofundamento e o alargamento dos vales teriam resultado de ciclos de incisão e pediplanação, causados portanto, por mudanças das condições climáticas e não por epirogênese, pelo menos desde o Pleistoceno médio. Os resultados indicaram pedogênese antiga mesmo nos solos mais jovens, desenvolvidos no fundo do vale durante o Holoceno. A presença da faixa de carvão queimado num latossolo do Terciário, é um indicador de queimadas frequentes. A idade do carvão fossil é 4730 ± 70BP. Resultados de outros trabalhos realizados no Brasil sugerem que o aumento do fogo num período de deposição se deve a um período mais seco entre dois mais úmidos. Sedimentação sobre a linha de carvão fóssil sugere um forte processo de redistribuição de material na superfície aplainada e portanto uma dinâmica de solo maior do que a geralmente referida.*

Palavras chave: gênese de solo, evolução de paisagem, paleoclima, Brasil Central.

1. Introduction

Soil genesis in Central Brazil is strongly related to landscape evolution. In general old soils have persisted on the uppermost erosion surfaces and younger soils have developed after valley incision during the Quaternary. Soil genesis can give valuable information on paleoclimatic conditions and thus be used to estimate the stages of landscape evolution. However, in Brazil only few studies have been carried out on this subject, e.g. SEMMEL & ROHDENBURG (1979), VEIT & VEIT (1985), EMMERICH (1988), LICHTE (1990). According to these authors soil development on the old erosion surfaces might well be more dynamic than generally assumed, suggesting intense soil redistribution on behalf of changing climatic conditions.

More such studies are particularly needed to highlight Cenozoic relief evolution, which is still very controversially discussed in Brazil. The main question of dispute is related to the driving forces behind denudation and subsequent incision. KING (1956), BRAUN (1971), LICHTE (1979) and KLAMMER (1981) and refer to positive epirogenesis and subsequent incision of the base level under constantly semi-arid conditions to be responsible for the formation of pediplanes and pediments, giving only minor importance to climatic fluctuations. Others (BIGARELLA & MOUSINHO, 1966, SEMMEL & ROHDENBURG, 1979; VEIT & VEIT, 1985; EMMERICH, 1988; GREINERT, 1992) believe that cycles between humid and semi-arid conditions especially during the Pleistocene and Holocene have led to deep chemical weathering during humid phases followed by denudation of the regolith during geomorphologically more active semi-arid epochs. With regard to this matter, NOVAES PINTO (1988) proposed that denudation and chemical weathering might have taken place concomitantly under semi-humid conditions in the sense of Büdel's double surfaces of levelling (BÜDEL, 1957).

At the NE border of the Paraná basin a complicated sequence of geological units was cut by Rio Araguari, a major tributary of Rio Paranaíba, reaching from Tertiary sediments on the Chapada top through mesozoic sediments to paleozoic rock at the valley base. According to the existing broad-scaled soil survey, the soils of these geological units are Oxisols, Inceptisols, and Alfisols, depending on their topographical position, parent material, and time of development (EMBRAPA, 1982). Soil development along this toposequence reflects landscape evolution and might be used to identify the stages of valley incision. However, no detailed relative or absolute age estimates of soil development have so far been attempted in this region.

The scope of this work is to elucidate soil genesis in the Triângulo Mineiro region and to correlate it with paleoclimatic phases by relative and absolute age estimates using pedological and mineralogical analysis and radiocarbon dating.

2. Materials and Methods

2.1. Study area

The study area is located close to Uberlândia, a city in the NW of the Triângulo Mineiro, Minas Gerais State, Brazil (Figure 1). The Triângulo Mineiro belongs to the southern part of the Cerrado region that covers close to $2 \cdot 10^6$ km² of Central Brazil.

Average annual temperature is 22 °C with a maximum in October and a minimum in July. Mean annual precipitation is about 1650 mm, concentrated in the rainy season from October through April when heating provokes instabilities of the Tropical Atlantic air mass resulting in intense frontal rains as well as heavy convective showers with high erosive energy (ROSA et al., 1991). Cooling during winter between May and September stabilises the Tropical Atlantic air mass and precipitation is strongly reduced, often ceasing completely for months.

Natural zonal vegetation is more or less dense Cerrado savanna (GOODLAND & FERRI, 1979). Gallery forests occur along the water courses. Extensive grazing is the dominating land-use form next to highly mechanised agriculture and reforestations. Pastures are mainly found in the medium to strongly dissected areas whereas agriculture and reforestations prevail on the tableland (Chapada).

Figure 1. Map of the study area located close to Uberlândia, MG, Brazil.

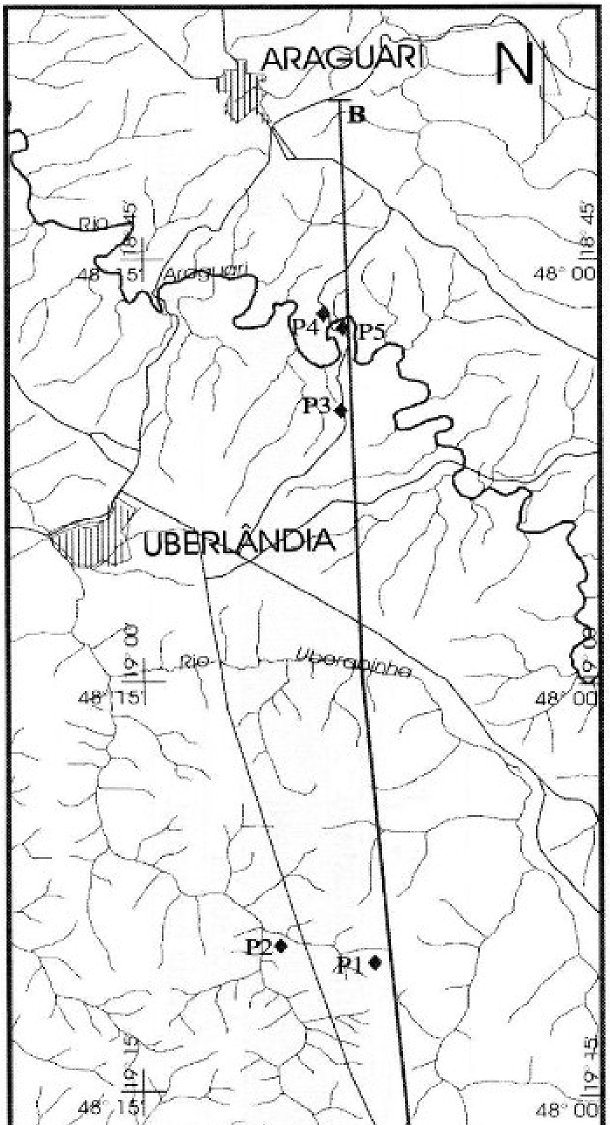
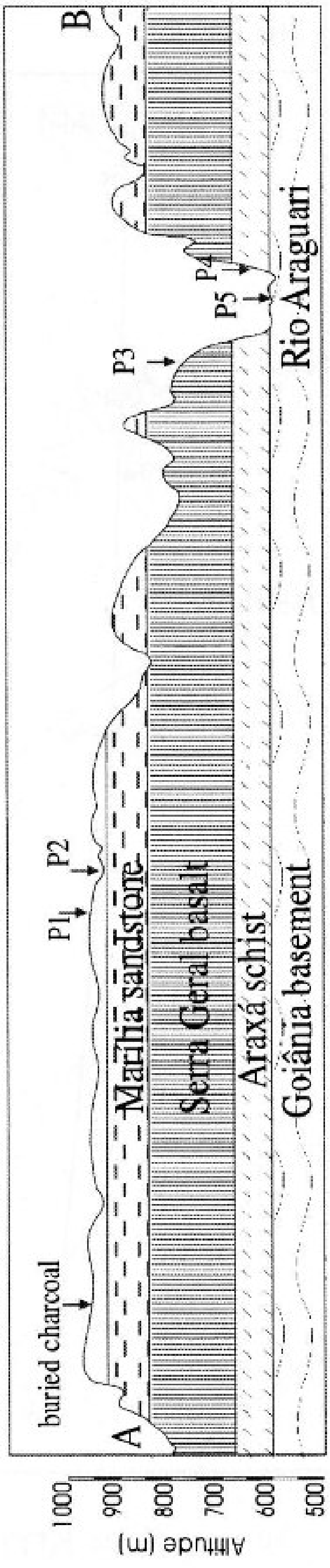


Figure 2. Schematic profile showing a cut through the major geological units and approximate sampling points of the study area.



2.2. Geological and paleoecological setting

The geological development of the Triângulo Mineiro has been described by HASUI (1969), BARBOSA et al. (1970), HASUI et al. (1975), BARCELOS et al. (1981), and BARCELOS (1984). More recently NISHIYAMA (1989) published a detailed stratigraphic chronology of the Uberlândia municipal area that corresponds to most of the study area.

The study area belongs to the NE border of the Paraná sedimentation basin that formed when the Archane Goiânia basement and Proterozoic sediments of the Araxá Group were lowered during the Devonian period. Outcrops of these two stratigraphic units, mainly granite, gneiss, and schists, appear close to the base level of Rio Araguari.

At the end of the Jurassic and lasting through Cretaceous the region was submitted to remarkable sedimentary and magmatic processes related to the Sul Atlantiano Reactivation of the South American Platform (SCHOBBENHAUS ET AL., 1984). The first stratigraphic unit belonging to this phase is the São Bento Group, represented by the Botucatu and Serra Geral Formations. The aeolian sandstones of the Botucatu desert are only present in isolated patches in the study area but the mafic magmatism of the Serra Geral Formation thereafter led to vast basalt layers in the Paraná basin. In the study area they attain 150 m thickness and appear along the rivers Araguari, Uberabinha, Tijuco, and Douradinho.

Beginning in Eocretaceous the sandy sediments of the Bauru Group were deposited in the Paraná basin as a result of the Alto Paranaíba uplift (SAD et al, 1971), which was still related to the Sul Atlantiano Reactivation. The 80-60 Ma old Marília Formation, the uppermost of the Bauru Group, reaches up to 100 m thickness in the study region and is exposed wherever the top sediments have been eroded. Sedimentation of the sandstones occurred under semi-arid climatic conditions with torrential rain events in alluvial fans. With calming of the tectonic activities pediplanation sculptured the Pratinha erosion surface (ALMEIDA, 1958), levelling all superficial strata. Concurrently the present drainage system was installed following ancient failure zones predominantly in NE-SW and E-W direction (LIMA, 1996). The Pratinha surface correlates to the final stage of the Sul Americana cycle (KING, 1956).

During lower Tertiary fine limnic sediments were deposited on top of the levelled Marília sandstones under humid tropical conditions. With formation of the Antarctic ice-shield beginning in mid Tertiary (FLOHN, 1985), semi-arid to arid tropical conditions prevailed followed by forest retreat (WOLFE, 1971) and installation of the Cerrado biome.

Tectonic reactivation between Oligocene and Miocene initiated the so-called Velhas cycle (KING, 1956). Accelerated linear erosion first dissected the Pratinha surface and denudation finally led to the establishment of a second planation surface. In the study area the Velhas surface only forms a pediment, inserted into the Rio Araguari valley and sustained by the Serra Geral basalts (BACCARO, 1994). According to BRAUN (1971) the Paraguaçu incision marks the beginning of the currently last erosion cycle leading to Rio Araguari's present base line.

Pleistocene changes between semi-arid and humid climate synchronous with ectropical cooling and warming cycles formed several pediments and terraces at different base levels (BIGARELLA & MOUSINHO, 1966) and strongly dissected the existing erosion surfaces. Climatic fluctuations during Holocene also point to phases of greater humidity and phases of stronger aridity in line with ectropical temperature variations, although less severe than during Pleistocene. These have been correlated with changing proportions of savannah and forest vegetation (cf. VAN DER HAMMEN, 1974; BEHLING, 1995). Present climatic conditions in Central Brazil are considered the most humid since 10,000 years (BEHLING, 1995).

2.3. Location of soil profiles and sampling procedures

The soils were selected according to morphological criteria along a toposequence from the Chapada to the valley floor and cover the main geological units (Figure 2). Only soils with comparable Brachiaria sp. pastures were selected because the natural vegetation changes from the Chapada to the valley floor. Profiles P1 and P2 are located close to each other on the Chapada at 950 m a.s.l. on the clay rich Tertiary sediments and at around 900 m on the sandy Marília Formation. Profiles P3, P4, and P5 are located further downhill on Serra Geral basalt, on Araxá micaschist, and on Quaternary alluvial sands, respectively. Classification was done according to Soil Taxonomy (SOIL SURVEY STAFF, 1994).

Buried charcoal for radiocarbon dating was found at 48°8'51" W and 19°20'43" S, in a ditch of 3 m depth and approximately 200 m extension opened for pipeline construction in July 1995. The site is located on the Chapada at 970 m altitude on clay-rich Tertiary sediments. Inclination is 1-2°. The soil is a fine textured dark-red Latosol according to the Brazilian classification system (EMBRAPA, 1981) and comparable to the Anionic Acrustox of profile P1. The buried charcoal forms a broken layer of small pieces with up to 2 cm diameter at around 1.0 m below soil surface. No charred material was found in above or below layers of the soil. The charcoal was picked by hand throughout the whole length of the ditch from both of its sides.

2.4. Analytical methods

Analyses were carried out on air-dried samples of the fine-earth fraction ground to < 0.1 mm. All results are given on a 105 °C dry base. For grain-size analysis the fine-earth was dispersed in 0.1 N NaOH. The sand fractions were weighed after wet-sieving while the clay and silt fractions were determined by sedimentation (EMBRAPA, 1979). C_{org} and N_{tot} were measured gas chromatographically (Elementar Vario EL). Soil pH was determined in H_2O and 1M KCl at a soil to solution ratio of 1:10 (EMBRAPA, 1979). Exchangeable Ca, Mg, and Al were extracted with 1 M KCl and exchangeable K was extracted with Mehlich 1 according to EMBRAPA (1979). The effective cation exchange capacity (CEC_e) was calculated as sum of exchangeable cations, whereas the potential CEC (CEC_p) was calculated as exchangeable bases plus exchangeable acididy at pH 7 (EMBRAPA, 1979). Well crystallised pedogenic Fe- and Al-compounds were extracted with dithionite-citrate-bicarbonate (DCB) solution (MEHRA & JACKSON, 1960), and extraction of x-ray amorphous Fe and Al oxides, hydroxides, and gels was carried out with acid oxalate solution according to BLUME & SCHWERTMAN (1969). Ca, Mg, K, Na, Al, and Fe of the different extracts were detected with a Shimadzu AA-660 AAS. Total element contents were determined by ICP-AES (GBC Integra XMP) after HF attack (LIM & JACKSON, 1982). Carbon isotopes of the charcoal were determined according to GEYH (1983).

Laser grain-size analysis was done with a Mastersizer-S (Malvern Instruments) grain-size analyser that covers a diameter range of 0.05 µm to 870 µm. NaOH dispersed fine-earth was sieved < 630 µm and < 63 µm. The 630-63 µm fraction was added to the cuvette in dry state and measured using the Fraunhofer approximation, while the < 63 µm fraction was added in solution and measured with the Mie theory using a particle refractive index of 1.53.

For powder x-ray diffraction of whole soil samples, ground fine-earth was fixed to the sample carrier with XRD amorphous hairspray, smoothened, and let dry. The < 2 µm fraction for determination of oriented clay was obtained after sedimentation of sonified fine-earth. The samples were treated with $MgCl_2$ and air-dried on the sample carrier. Subsequent treatment with ethylene glycol, K, and K+560 °C was done for peak differentiation. A D5000 X-ray diffractometer (Siemens) running with a CuK-α radiation at a scanning rate of $2°$-2θ per minute was used. Identification of reflections followed BROWN AND BRINDLEY (1980).

Thin sections for polarisation microscopy of the fine sand and coarse sand fractions were obtained after bonding the grains to a glass slide with epoxy resin and polishing to 30 µm thickness. Mineral composition was estimated from the fine sand fraction (50-250 µm) only.

2.5. Weathering indices

The release of silicate bound Fe and Al from primary minerals and the formation of pedogenic Fe and Al compounds is an important process during soil weathering that has recently been used for relative age estimation by BÄUMLER ET AL. (1996). In the initial phase of soil formation there is a rapid accumulation of pedogenic Fe (Fe_d). With time the primary minerals are exhausted and weathering resistant oxides first increase and finally reach a steady state (ANIKU & SINGER, 1990). Concomitantly pedogenic Fe compounds become increasingly crystallised (dehydrated) under oxidizing conditions. Therefore the ratio of well (Fe_d-Fe_o) to badly crystalline pedogenic iron (Fe_o) may be used as an indicator of the weathering degree within a pedon. as well as of relative age between soils (ALEXANDER, 1974; ARDUINO ET AL., 1984).

KRONBERG & NESBITT (1981) have defined theoretical weathering indices on element basis that separate between chemical and physical weathering and give an estimate of soil transformation. The ratio of ($CaO + Na_2O + K_2O$) / ($Al_2O_3 + CaO + Na_2O + K_2O$) is plotted against the ratio ($SiO_2 + CaO + Na_2O + K_2O$)/($Al_2O_3 + SiO_2 + CaO + Na_2O + K_2O$). Whereas the first ratio (Index B) represents the breakdown of feldspars which is accompanied by the formation of secondary minerals, the second ratio (Index A) describes the enrichment of durable minerals such as quartz and gibbsite. Therefore, ultimately, Index B will reach zero when all primary minerals are destroyed, and Index A will attain either zero (gibbsite) or one (quartz) depending whether chemical or physical weathering prevails.

3. Results

3.1. Chemical and physical characterisation

Changes of the chemical properties within each profile occur gradually (Table 1). pH (H_2O) is low in all soils except profile P4, pH (KCl) mostly being close to one unit lower. The Bo horizon of P1 is an exception indicating anionic charge characteristics in the subsoil. CEC_e is generally low and decreases with depth, reflecting the low pH and dominance of low activity clays or low clay contents. In the subsoils of P3 and P4, however, CEC_e rises again on behalf of less intense weathering. CEC_p is considerably higher on account of variable charge given by the soil organic matter next to Fe and Al oxides and hydroxides.

The particle size distribution (Table 1) reflects the predominance of fine-earth (< 2 mm) in all soils. However, in horizon Bo/C of profile P3 25 % of the soil volume are in form of easily breakable basalt cherts with about 50 mm diameter, and horizon 2C/Bw of profile P4 is a stoneline with 70 % quartz and quartzite cherts ranging from 50 mm to 200 mm diameter. In addition the surface horizons of profiles P3, P4, and P5 reflect hillwash. In the fine-earth fraction the clay content increases slightly with depth, decreasing again close to the weathering front. In P4 a profile discontinuity was established between horizon 3Bo and 4Bw due to the sharp decrease in clay content (KLEBER, personal communication).

Table 1. Classification, coordinates, and main analytical data of the soils from the Rio Araguari toposequence.

Profile No., Subgroup Location Altitude, Exposition	Horizon	Depth	Colour moist	pH		C_{org}	C/N	CEC_e	CEC_p	Particle Size Distribution			
		(cm)		H_2O	KCl	(g kg^{-1})		(cmol$_c$ kg^{-1})		> 2/< 2 (%)	Sand	Silt (%)	Clay
P1 Anionic Acrustox	Ap	0–20	7.5YR 3/4	5.3	4.7	2.5	18	2.48	5.65	–/100	19	14	67
48°07'17"W, 19°09'03"S	A2	20–40	7.5YR 3/6	5.5	4.5	1.7	18	1.10	3.72	–/100	15	13	72
950 m, W 1°	BoA	40–63	6.3YR 3/6	5.2	4.6	1.3	18	0.35	2.67	–/100	15	11	74
	Bo	63–150+	5YR 3/6	5.1	5.2	1.0	18	0.17	1.65	–/100	16	8	76
P2 Typic Haplustox	Ap	0–18	10YR 3/4	5.4	4.5	0.8	17	1.30	4.19	–/100	81	0	19
48°08'47"W, 19°12'44"S	A2	18–30	10YR 3/5	5.4	4.4	0.6	17	0.65	3.41	–/100	81	0	19
895 m, W 2°	BoA	30–55	10YR 3/6	5.3	4.3	0.5	18	0.44	2.58	–/100	80	0	20
	Bo	55–155+	7.5YR 3/6	5.3	4.6	0.4	18	0.11	1.68	–/100	77	1	22
P3 Rhodic Haplustox	Ap	0–20	10R 3/2	5.2	4.2	1.9	14	3.96	9.86	5/95	12	22	66
48°08'23"W, 18°49'36"S	Bo	20–90	10R 3/2	5.3	4.4	0.5	15	1.79	6.08	–/100	7	24	69
730 m, NNE 4-5°	Bo/C	90–185+	10R 3/2	5.3	4.0	0.2	13	7.18	9.00	25/75	9	31	60
P4 Typic Haplustoll	Ap	0–20	10YR 2/2	5.8	4.6	2.5	13	6.93	12.44	5/95	59	17	24
48°08'10"W, 18°47'08"S	Bw	20–45	10YR 3/3	6.2	5.0	1.4	14	6.25	9.35	10/90	60	16	24
605 m, W 4°	2C/Bw	45–60	7.5YR 3/4	6.4	5.1	1.1	14	5.69	8.86	70/30	60	15	25
	3Bo	60–105	5YR 3/6	6.7	5.5	0.5	15	4.76	6.78	–/100	49	19	32
	4Bw	105–145	10YR 4/4	6.7	5.1	0.2	15	6.79	8.51	–/100	72	21	7
	4CB	145–245+	10YR 4/4	6.9	4.8	0.0	–	6.24	7.79	–/100	86	12	2
P5 Fluventic Dystropept	Ap	0–30	10YR 3/4	5.1	4.0	1.0	13	1.69	4.77	5/95	81	6	13
48°08'10"W, 18°47'51"S	Bw1	30-60	8.8YR 3/4	5.2	4.1	0.5	12	1.47	3.83	–/100	80	5	15
585 m, SE 10°	2Bw2	60–100	6.3YR 3/4	5.5	4.5	0.3	11	1.49	3.83	–/100	72	7	21
	2Bw3	100–150+	6.3YR 3/6	5.5	4.5	0.2	11	1.38	3.92	–/100	66	8	26

Total Fe contents are closely related to the parent material and generally rise slightly with depth (Table 2). Pedogenic Fe contents depend on substrate and weathering degree and lie between 40 % and 70 % of total Fe in all but horizons 4Bw and 4CB of profile P4, suggesting an overall advanced stage of weathering. Possibly a steady state is achieved when around 70 % of total Fe are present in form of oxides and hydroxides. Oxalate extractable Fe makes up only 1-9 % of Fe_t and is normally greatest in the surface horizon, possibly because higher organic matter contents in the surface soil reduce crystallisation by complexation. In the subsoil horizons of profiles P3 and P4 Fe_o increases again because of freshly liberated primary Fe.

The ratio of well to badly crystalline pedogenic Fe (Fe_{d-o}/Fe_o), suggested by ALEXANDER (1974), precisely shows the horizon of maximum weathering degree in all soils. In profiles P1, P2, and P3 this corresponds to the lowermost horizons because the weathering front is not attained, whereas in profiles P3 and P4 the ratio is reduced near the C horizon. In addition, the maximum $(Fe_d-Fe_o)/Fe_o$ ratio of each soil decreases from the Chapada to the valley floor, indicating a continuous reduction of weathering degree and thus age. It seems that under conditions of prolonged soil development, this ratio might reflect weathering intensity better than the $(Fe_d-Fe_o)/Fe_t$ ratio proposed by ARDUINO ET AL. (1984) because the amounts of x-ray amorphous Fe have become so small.

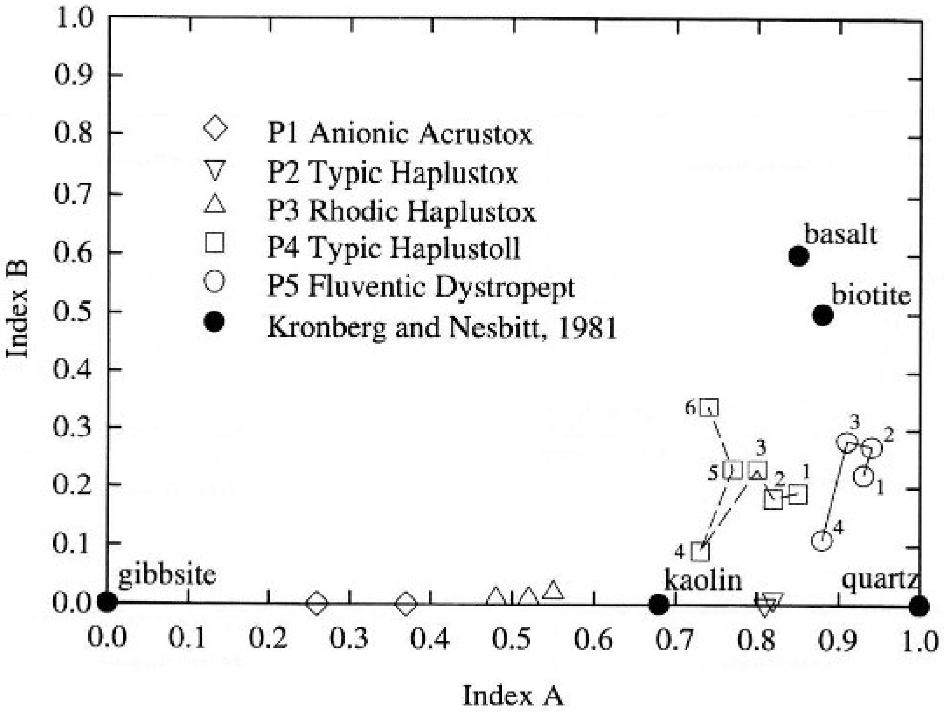
Weathering indices A and B (Figure 3, Table 2) generally confirm these results. In profiles P1 to P3 unstable primary minerals are practically absent, showing the dominance of gibbsite in the case of P1 and that of quartz in P2, while P3 should be considered predominantly kaolinitic. Profiles P4 and P5 present some weatherable minerals, even in the most developed horizons. Profile P5 further indicates stronger influence of physical weathering due to the enrichment of quartz caused by fluvial sedimentation.

Table 2. Analytical data, weathering indices, and whole soil powder x-ray diffraction intensities of the soils from the Rio Araguari toposequence.

Subgroup Horizon	Fe_t	Fe_d	Fe_o	Fe_d/ Fe_t	(Fe_d-Fe_o)/ Fe_o	quartz	illite/ biotite	kaolinite	gibbsite	goethite	hematite/ magnetite	Index A	Index B
	—	(g kg^{-1})	—										
P1 Anionic Acrustox													
Ap	82.2	54.4	1.8	0.66	29	++	–/–	+++	+++	+	tr. /–	0.26	0.00
Bo	86.7	58.0	0.6	0.67	96	++	–/–	+++	+++	+	tr. /–	0.37	0.00
P2 Typic Haplustox													
Ap	28.1	16.4	0.8	0.58	20	++++	–/–	+	+	+	–/–	0.82	0.01
Bo	33.0	19.2	0.3	0.58	63	++++	–/–	+	+	+	–/–	0.81	0.00
P3 Rhodic Haplustox													
Ap	246.2	150.8	3.3	0.61	45	++	–/–	+++	+	+	+/+	0.52	0.01
Bo	262.0	159.2	3.6	0.61	43	+	–/–	+++	++	++	++/+	0.48	0.01
Bo/C	263.7	144.0	4.1	0.55	34	+	+/–	+++	+	++	++/+	0.55	0.02
P4 Typic Haplustoll													
Ap	35.8	16.8	3.3	0.47	4	+++	+/ tr.	++	tr.	+	–/–	0.85	0.19
Bw	39.1	15.8	2.7	0.40	5	+++	+/+	++	tr.	+	–/–	0.82	0.18
2C/Bw	53.8	21.3	1.7	0.40	12	+++	+/+	++	+	+	–/–	0.80	0.23
3Bo	60.0	33.4	1.4	0.56	23	+++	+/+	+++	+	+	–/–	0.73	0.09
4Bw	69.7	17.9	1.1	0.26	15	+++	++/++	++	tr.	+	–/–	0.77	0.23
4CB	92.9	18.9	1.4	0.20	13	++	–/+++	++	–	–	–/–	0.74	0.34
P5 Fluventic Dystropept													
Ap	25.9	12.7	1.8	0.49	6	++++	+/–	+	–	tr.	–/–	0.93	0.22
Bw1	27.5	16.5	1.8	0.60	8	++++	+/–	+	–	tr.	–/–	0.94	0.27
2Bw2	37.0	23.1	1.6	0.62	13	++++	+/–	++	tr.	+	–/–	0.91	0.28
2Bw3	36.3	26.0	1.7	0.72	14	++++	+/–	++	tr.	+	–/–	0.88	0.11

not detected: –   0-1 %: traces   2-10 %: +   11-30 %: + +   31-70 %: + + +   > 70 %: + + + +

Figure 3. Weathering indices of soils along a toposequence of Rio Araguari and reference materials according to Kronberg and Nesbitt (1981).

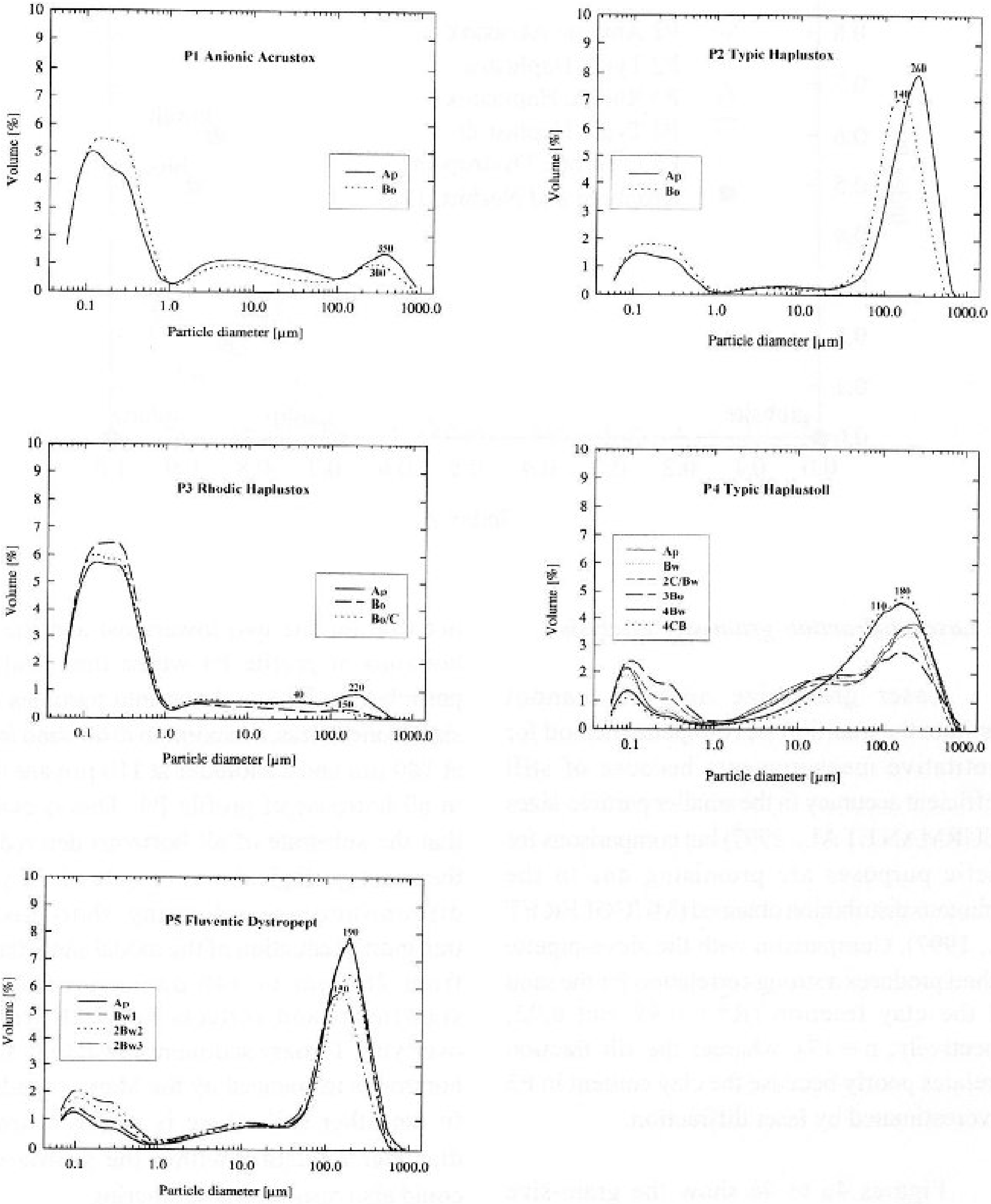


3.2. Laser diffraction grain-size analysis

Laser grain-size analysis cannot substitute the tradition sieve-pipette method for quantitative measurements because of still insufficient accuracy in the smaller particle-sizes (BUURMAN ET AL., 1997) but comparisons for genetic purposes are promising due to the continuous distribution obtained (MUGGLER ET AL., 1997). Comparison with the sieve-pipette method produces a strong correlation for the sand and the clay fraction ($R^2 = 0.99$ and 0.92, respectively; $n = 17$), whereas the silt fraction correlates poorly because the clay content in P3 is overestimated by laser diffraction.

Figures 4a to 4e show the grain-size distribution of the studied profiles. Soil weathering is reflected by an increase in clay content and a loss in the sand fraction. This is not true for the two lowermost and the other horizons of profile P4 where fine sand sized particles are broken down into particles of silt size. Nonetheless, a maximum in the sand fraction at 180 µm and a shoulder at 110 µm are visible in all horizons of profile P4. This is evidence that the substrate of all horizons derived from the same geological unit in spite of the profile discontinuities, indicating short distance transport. Reduction of the modal sand diameter from 260 µm to 140 µm in profile P2 is significant and reflects hillwash from the overlying Tertiary sediments. In P3 the surface horizon is influenced by the Marília sandstone. In the other soils there is merely a trend to diameter reduction within the profile which could also result from weathering.

Figure 4a-4e. Particle-size distribution of soils along a toposequence of Rio Araguari as determined by laser diffraction.



3.3. X-ray diffraction analysis

Reflection intensities of x-ray diffractograms may not be quantitatively analysed because of each mineral's differing diffractive abilities but they can be used to compare relative abundances (HARDY & TUCKER, 1989). Results of powder XRD indicate advanced to extreme weathering in the soils in spite of the presence of some primary weatherable minerals (Table 2). Feldspars could not be clearly identified in any scan. Quartz strongly dominates the mineralogy of profiles P2 and P5 reflecting their high sand contents. Yet, while in P2 minor secondary minerals consist only of kaolinite and oxides, in P5 illites are present and oxides merely occur in traces. Profiles P1 and P3 have strong kaolinite intensities along with gibbsite in P1 and Fe oxides, mainly hematite and goethite, in P3, suggesting extreme weathering of a very fine substrate. However, in horizon Bo/C of profile P3 some illite is still present. Profile P4 shows predominant influence of quartz in all but horizon 4CB. Micas occur in all horizons to a significant degree, strengthening the impression that the whole solum derived from the Araxá schist in spite of profile discontinuities. The presence of fair amounts of kaolinite even in horizon 4CB indicates an advanced stage of soil formation.

Scans of oriented clay samples generally confirm strong weathering of the soils (Table 3). However, the clay composition of the sandy soils becomes more apparent. Gibbsite dominates the clay fractions of P1 and P2. Profile P3 reflects the gibbsite's decreasing abundance concomitant with increasing kaolinite. The clay fraction of P4 is apparently dominated by kaolinite and illite, whereas kaolinite again prevails in P5 despite a considerable amount of high activity clays. Traces of vermiculite were only detected in horizon 3Bw of P4, suggesting the mineral's instability under the given conditions.

3.4. Petrography

Thin sections of the sand fraction reveal the predominance of quartz next to varying proportions of opaque materials, mainly iron oxides, and less weathering resistant minerals, in their majority micas and feldspars (Table 3). The quartz grains are apparently derived from distinct localities because of their differing roundness and light breaking characteristics. Many of the angular quartz grains show undulose extinction indicating metamorphic stress (HARWOOD, 1989) whereas the rounded grains reflect long distance transport but show straight extinction. The third group consists of rounded quartz grains stained with hematite showing weak undulose extinction. They are frequently broken into numerous subcrystals which might explain the high content of angular quartz grains in the fine sand fraction. Rounded grains of the clear (straight extinction) and hematite stained kind are most abundant in profiles P1 and P2 and typically of coarse sand size what excludes aeolian transport. On the other hand, in P4 only undulose angular quartz, inherited from the Araxá schist, is present. In P5 rounded quartz again exists in significant amount. Opaque concretions coming from the basalt are enriched in P3. Minor contents are also found in P1. Araxá schist derived biotite dominates the subsoil sand fraction of P4. Feldspars, above all albites, are present in low quantities, too. Nonetheless, even in horizon 4CB, feldspars and micas are practically all strongly decayed. In profile P5, additionally weathered muscovite and augite are present that were probably derived from the Precambrian basement. These findings indicate deep etching of the primary rock during the present sub-humid climate.

Table 3. X-ray diffraction analysis of oriented clay (< 2 µm) and polarisation microscopy of the fine sand fraction (50-250 µm) from the Rio Araguari toposequence.

Soil Subgroup	Horizon	XRD of oriented clay					Polarisation microscopy of fine sand				
		kaolinite	illite/ biotite	gibbsite	goethite	hematite	quartz		opaque	mica	feldspar
							(%)	a:r:s[a]		(%)	
P1 Anionic Acrustox	Bo	++	–	+++	++	+	>80	60:20:20	10	–	–
P2 Typic Haplustox	Bo	++	–	++++	++	–	>90	30:50:20	<5	–	–
P3 Rhodic Haplustox	Bo	++	+	+++	+	++	<50	45:45:10	>50	tr.	tr.
	Bo/C	+++	+	++	+	++	<30	60:30:10	>70	tr.	<5
P4 Typic Haplustoll	Bw	+++	+++	+	+	–	80	90:10:0	tr.	<10	<10
	2C/Bw	+++	+++	+	+	–	n.d.[b]	n.d.	n.d.	n.d.	n.d.
	3Bo	+++	+++	++	+	–	>60	100:0:0	<10	>20	<5
	4Bw	+++	+++	+	+	–	<50	100:0:0	–	>50	<10
	4CB	+++	+++	–	tr.	–	<30	100:0:0	–	>70	<10
P5 Fluventic Dystropept	Bw1	+++	++	+	++	–	n.d.	n.d.	n.d.	n.d.	n.d.
	2Bw2	+++	++	+	++	–	<90	60:35:5	<5	<5	<10
	2Bw3	+++	++	+	++	–	n.d.	n.d.	n.d.	n.d.	n.d.

not detected: – 0-1 %: traces 2-10 %: + 11-30 %: + + 31-70 %: + + + > 70 %: + + + +

a) a:r:s angular : round : Fe-stained

b) n.d. not determined

3.5. Radiocarbon analysis

Given the scarcity of datable material in the region and thus the difficulty in assigning absolute age to soils, any datable substrate is of great value to elucidate landscape development. The buried charcoal layer permits to reconstruct the soil dynamics on the Chapada since its deposition and is likely to by applicable to the history of profile P1. Radiocarbon age of the charcoal (Hv 21306) is given as 4730 ± 70 BP. The presence of charcoal in a subsurface horizon is evidence of frequent burning at the time of deposition, suggesting rather dry environmental conditions. Nonetheless, the water regime must have permitted the growth of woody species as the $\delta\ ^{13}C$ value of -26.1 ‰ is typical of C_3 plants (STOUT ET AL., 1981). Cerrado (sensu stricto) vegetation has a $\delta\ ^{13}C$ value near -20 ‰ (NEUFELDT, 1998), reflecting the presence of both trees and grasses with C_4 metabolism. As a possible grass component was not preserved, the past vegetation cannot be fully deduced from the charred material.

4. Discussion

Chemical analyses and weathering indices show generally decreasing soil development from the Chapada to the valley floor. Weathering is extreme in profiles P1 and P2 so that the soils must be considered very old. Bearing in mind that limnic sedimentation on the Pratinha surface ended with climate change during Tertiary, soil development of profile P1 could already have begun short after whereas P2 developed after erosion of the top layers. Both soils are probably connected to the beginning Velhas cycle (KING, 1956). The cycle ended when the Velhas surface, forming a pediment at approximately 850 m to 750 m altitude in the Rio Araguari valley, was dissected again. Profile P3 inherits an intermediate position and developed at the beginning of the incision phase of the Paraguaçu cycle. Profiles P4 and P5 are comparatively young soils that developed when Rio Araguari was already close to its present base level. Nonetheless, even these young soils are already in an advanced stage of mineral decomposition, reflecting intense weathering rates during Holocene.

Although weathering indices mainly indicate continuous soil genesis since the upper Tertiary, profile discontinuities, mineralogical analysis, and radiocarbon dating further allow to differentiate this picture. By giving a more detailed view of pedogenesis partial reconstruction of formation time and climatic conditions is possible. Therefore a broad chronological assignment is attempted in the following (Table 4).

The fossil 3Bo horizon of profile P4 is characterised by Fe oxide and gibbsite enrichment suggesting prolonged soil development, although charge characteristics do not completely satisfy the requirements of a diagnostic oxic horizon according to Soil Taxonomy (SOIL SURVEY STAFF, 1994). Nonetheless, Oxisol development is a long-lasting process, even in the tropics (DRIESSEN & DUDAL, 1991), necessitating high temperatures and strong leaching rates, at least during part of the year. This implies that climatic conditions during its formation must have been sub-humid to humid. These conditions are possibly given under the present climate but it seems very unlikely that the fossil 3Bo horizon could have formed during Holocene. However, a proof cannot be given because it was not possible to determine the horizon's age directly by radiocarbon dating due to its low C_{org} contents.

Table 4. Broad chronology of soil development, environmental impacts, and paleoclimate of the study area.

Time	Soil development and environmental impact	Climate
5000 BP to present	erosion, deep chemical weathering	humid, tropical
around 5000 BP	frequent fires	drier
early Holocene	deep chemical weathering	humid
late Pleistocene	stoneline formation	dry
Pleistocene interglacial	Oxisol development	humid, tropical
early Pleistocene	Oxisol development on Velhas pediment	sub-humid - humid
late Tertiary	Oxisol development on Pratinha surface	sub-humid - humid

Yet, according to BIGARELLA & AB'SÁBER (1964) all over Brazil frequently stonelines occur that formed at the end of the latest ectropical glaciation under semi-arid to arid climate by washing and blowing away of the fine-earth. These can be used as reference layers between Pleistocene and Holocene. Assuming that the stoneline (2C/Bw) above the fossil 3Bo be such a reference layer, formation of the ancient Oxisol must have taken place during a period of high chemical weathering activity prior to the latest ectropical glaciation, probably during the Wisconsin-Illinoian interglacial.

After further valley incision the whole solum, including horizons 2C/Bw and 3Bo, slid over the apparently young 4Bw horizon. According to KLEBER (personal communication) this is possible without disturbing the dislocated horizons. Vertical dislocation of the solum certainly occurred within the extension of the Araxá schist due to the profile's uniform mineralogy and thus did not surpass 100 m. Recent hillwash led to the final profile stratigraphy by posing horizons Ap and Bw on top of the stoneline.

Further evidence of climate change during Holocene comes from profile P5. Sedimentation of a finer substrate in the subsoil indicates a drier phase at deposition time due to a lower water table of Rio Araguari. The coarser textured surface sediments were later deposited on behalf of higher erosive energy after a change to greater humidity. However, lacking datable material no absolute chronology is so far possible.

The age of the buried charcoal layer on the Chapada possibly indicates a climate change to a drier environment at deposition. The savanna could therefore have been more open than today, but certainly no complete change to grassland occurred because the charcoal derived from woody species. Microscopical analysis of the sand fraction of profile P1, which is comparable to the soil on top of the charcoal suggests that sedimentation occurred in suspended form and not after aeolian transport because rounded quartz dominates the coarse sand fraction whereas angular quartz grains prevail in the fine sand. Under aeolian conditions the inverse would be expected. Additionally, fine sand to total sand ratios between horizons remain constant in all soils and thus do not support changes in transport dynamics (EVANS AND ADAMS, 1975). Thus, the moister climate since charcoal deposition must have permitted the accumulation of 100 cm in only 5000 a on a near to flat relief. This accumulation may have been accelerated also due to bioturbation, especially by termites.

Findings of other authors working in Central Brazil sustain the interpretation of a dry phase around 5000 BP and greater humidity since then as proposed here (SERVANT ET AL., 1989; BEHLING, 1995). Comparable results for southern Brazil come from BIGARELLA (1971) and JERARDINO (1995). ABSY (1979) and VAN DER HAMMEN (1982, 1983), working in the Amazon basin and the Colombian Llanos, respectively, further corroborate to the subcontinental extension of climate change. As the time of charcoal deposition corresponds well with maximum glacier advance in Argentina and Chile at 4600 BP (MERCER, 1984) and evidence of cooling all around the world (RÖTHLISBERGER, 1986), the correlation between ectropical cooling and tropical dryness (BIGARELLA & AB'SABER, 1964) gains further weight.

Profile discontinuities of late Pleistocene age, where morphologically or chemically different material has been deposited on top of apparently old surfaces in Central Brazil have been described by EMMERICH (1988) and LICHTE (1990). SEMMEL & ROHDENBURG (1979) found similar profile discontinuities in southern Brazil. Yet, all workers proposed aeolian transport as driving force of sedimentation. Possibly late Pleistocene dryness (BIGARELLA & ANDRADE, 1965), was more accentuated than during the Neoglacial, favouring wind erosion.

The results support changing climatic conditions between dry and humid at least since the upper Pleistocene in line with SEMMEL & ROHDENBURG (1979) and VEIT & VEIT (1985). Climate changes for earlier periods can, however, not be sustained with the presented data so that it remains unclear whether primarily climatic effects (BIGARELLA & ANDRADE, 1965; BIGARELLA & MOUSINHO, 1966) or epirogenesis (KING, 1956; BRAUN, 1971) are responsible for incision and subsequent planation during Tertiary and early Quaternary. Nonetheless, observing the accentuated effects of recent climatic changes on the erosion surfaces and taking into consideration the extended time spans needed for their formation, it seems possible that planation occurred not only under semi-arid to arid conditions but also in a sub-humid climate in the sense of Büdel's double surfaces of levelling (BÜDEL, 1957) as already proposed by NOVAES PINTO (1988).

5. Conclusions

Paleoclimatic changes have strongly affected soil development in Central Brazil at least since mid Pleistocene. Possible earlier climate changes are suspected but could not be proved. Further studies are therefore needed to elucidate Tertiary and early Quaternary landscape evolution and to add more information to the suspected chronology.

On the Chapadas Holocene soil redistribution during sub-humid phases is intense in spite of small inclinations while in the valleys accelerated erosion occurs. Chemical weathering is intensive. Conditions of strong chemical weathering apparently occurred since the Tertiary and lasted long enough to produce Oxisols close to the recent valley floor of Rio Araguari. These Oxisols probably developed during humid phases of the last Pleistocene.

During dry phases physical erosion prevailed forming stonelines that are frequently buried by recent hillwash. However, on the Chapadas no indicators were encountered that could give evidence how dry periods affected soil formation there.

In order to further elucidate landscape development in Central Brazil, the evolution of the Tertiary erosion surfaces is of particular significance, especially during late Pleistocene and early Holocene. Radiocarbon dating of fossil peat from the Chapadas and correlation with pollen analysis would be of overall importance in this context.

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