The carbon isotope record in soils along a forest-cerrado ecosystem transect: implications for vegetation changes in the Rondonia state, southwestern Brazilian Amazon region

L.C.R. Pessenda,[1] B.M. Gomes,[2] R. Aravena,[3] A.S. Ribeiro,[4] R. Boulet[5] and S.E.M. Gouveia[1]

([1]Laboratorio de ^{14}C - CENA, USP, 13400 - 970, Piracicaba, SP, Brazil; [2]Universidade de Rondonia, Campus de Ji-Parana e Porto Velho, Rondonia, Brazil; [3]Quaternary Research Institute and Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1; [4]Universidade de Sergipe, Aracaju, 491000-000, Sergipe, Brazil; [5]ORSTOM, Instituto de Geosciencias, 05508-900, USP/NUPEGEL, Brazil)

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Abstract: This paper presents carbon isotope data on soil organic matter (SOM) collected along an ecosystem transect that includes a wooded savannah (cerrado), a tropical semideciduous forest (cerradão), a forest transition type and a tropical forest. The study area is located in the Rondonia state, southwestern Brazilian Amazon region. ^{14}C data of total soil organic matter and charcoal indicate that the organic matter in these soils is at least Holocene in age. The forest and forest transition sites are characterized by $\delta^{13}C$ soil depth profiles generated typically by C_3 plants, indicating no major changes in plant communities have occurred in this region during the time period represented by the isotope data. In contrast, the cerrado and cerradão have experienced significant vegetation changes during the Holocene. The $\delta^{13}C$ data (−30‰ to −27‰) obtained in the deepest part of the profile at the cerradão site show the expansion of the C_3 forest vegetation into this region during early Holocene. A vegetation change consisting of increased C_4 plant influence is reflected in the ^{13}C-enriched values (−19‰ to −16.0‰) at both sites during the middle Holocene. The recent part of the ^{13}C record shows a clear expansion of C_3 vegetation, particularly at the cerradão site. The regression/expansion of the forest and savannah vegetation documented at the cerradão and cerrado sites is probably related to changes from a humid to a drier climate and a return to more humid conditions and is in agreement with palaeoclimatic information reported for Brazil and the Bolivian Altiplano. This study suggests that large areas in the Amazon basin have been affected by vegetation changes during the Holocene and that soil organic matter in the transition areas between savannah and forest ecotones contains a valuable palaeorecord of vegetation changes in the Amazon region.

Key words: Carbon isotopes, soil organic matter, cerrado-forest ecosystem, vegetation changes, Rondonia state, Amazon region, Holocene.

Introduction

The Amazon region is one of the key ecosystems that are being investigated as part of the Global Change Research Program. Most of the research efforts have focused on the understanding of the link between climate changes and past vegetation in the Amazon region during the Quaternary (Liu and Colinvaux, 1985; Bush and Colinvaux, 1988; Markgraf, 1989; Absy *et al.*, 1991; Colinvaux *et al.*, 1996). Palaeoenvironmental studies done on peat, lake sediments and soil organic matter (Turcq *et al.*, 1993; Desjardins *et*

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al., 1996; Pessenda *et al.*, 1997; 1998) associate with pollen records (Van der Hammen, 1972; Absy and Van der Hammen, 1976; Absy *et al.*, 1991; Colinvaux *et al.*, 1996) and palaeofauna (Rancy, 1993) show several periods of expansion/regression between forest and savannah vegetation during the late Quaternary. Studies on birds and lizards in the Amazon region (Haffer, 1969; Vanzolini and Willians, 1970) concluded that in some dry periods during the Pleistocene the tropical forest was reduced to isolated areas or refuges, where animal and vegetation species survived under harsh climatic conditions.

Studies on soil organic matter dynamics using carbon isotopes as indicators have also been successfully applied in different parts of the world to infer information about the link between vegetation changes and climate during the late Quaternary (Krishnamurthy *et al.*, 1982; Schwartz *et al.*, 1986; Schwartz, 1988; Guillet *et al.*, 1988; Ambrose and Sikes, 1991). This approach had also been used in different areas in Brazil to document vegetation changes during the Holocene (Volkoff and Cerri, 1987; Desjardins *et al.*, 1991; 1996; Victoria *et al.*, 1995; Pessenda *et al.*, 1996a; 1996b; 1997; 1998; Martinelli *et al.*, 1996). The application of carbon isotopes in the Amazon basin, that is based on the different ^{13}C composition of C_3 and C_4 plants (Smith and Epstein, 1971; Boutton, 1991) and its preservation in soil organic matter (SOM), is potentially useful for documenting changes in terrestrial vegetation in this region (Martinelli *et al.*, 1991).

This paper presents data collected along a transect covering four different types of vegetation communities, representative of the ecosystem's diversity that presently exists in the Amazon region. These include a wooded savannah (cerrado), a tropical semideciduous forest (cerradão), a forest transition type and a tropical forest. Recent carbon isotope studies on SOM of several sites in the Amazon region (Desjardins *et al.*, 1996; Sanaiotti, 1996; Pessenda *et al.*, 1997; 1998) suggest that vegetation communities in the cerrado and cerradão ecosystems should be more sensitive to climate changes. Therefore, soil in these areas should preserve a better record of past vegetation changes, that can be used to study the link between climatic changes and its impact on vegetation communities.

Materials and methods

The study area is located in the Rondonia state, northwestern part of Brazil (Figure 1). The sampling sites are located close to the

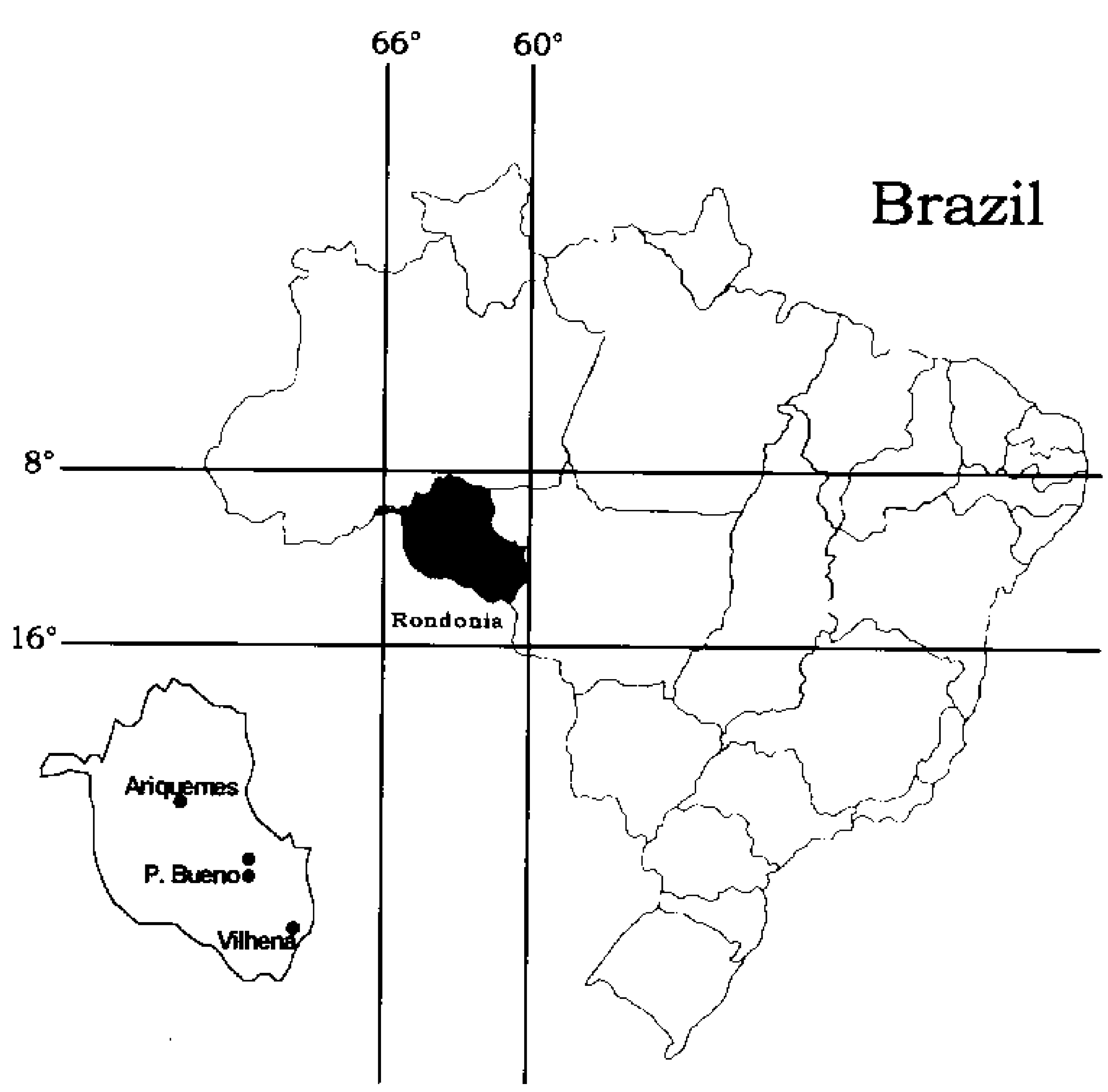

Figure 1 Map of Brazil showing the study sites in the state of Rondonia.

city of Vilhena (12°42'S and 66°07'W), representative of the cerrado vegetation and defined by Ledru (1993) as a wooded savannah. Goodland and Polard (1973) considered the cerrado *sensu strictu* as a vegetation with trees of about 6 m, density of 1400 trees per ha and total basal area of 76 000 cm²/ha. Grass species including *Trystachia* sp., *Panicum* sp., *Eleusine* sp. and *Bulbostylis* sp., are interspersed with trees, mainly *Curatella americana*, *Miconia* sp. and *Cassia* sp. The other sites are near Pimenta Bueno (transition site) under vegetation of cerradão (11°49'S and 61°10'W) and natural forest (11°46'S and 61°15'W), and in Ariquemes (10°10'S and 62°49'W) under vegetation of natural forest (Figure 1). Goodland and Polard (1973) considered the cerradão a vegetation with trees of approximately 9 m, density of about 3000 trees/ha and total basal area of 300 000 cm²/ha. This vegetation can be considered as a transitional state between the dense evergreen forest and the savannah and is denominated as tropical semideciduous forest. Some of the dominant C_3 plants in these forested sites are *Miconia* sp., *Piper* sp., *Cecronia* sp., *Protium* sp., *Andira* sp., *Inga* sp. and *Euterpe precatoria*. The soil in Vilhena is a Latossolo Vermelho-Amarelo (Brazilian classification), whereas Latossolo Vermelho-Escuro (cerradão site) and Latossolo Amarelo (forest transition) soils are located in Pimenta Bueno. These soils are Oxisols according to the Soil Taxonomy (USDA) classification. In Ariquemes, Podzólico Vermelho-Amarelo (Ultisol in the USDA classification) soil dominates. The distance between Vilhena and Pimento Bueno is about 200 km and from Pimenta Bueno to Ariquemes is about 400 km. In the transition cerradão-forest, the distance between the study sites is about 40 km.

Soil samples were collected from excavations located in areas under the four types of vegetation communities. Soil sampling involved the collection up to 10 kg of material at 10 cm intervals to maximum depth of 200 cm. Samples were dried at 60°C to constant weight, and root and plant remains were discarded by hand-picking. Any remaining plant debris was removed by flotation in HCl 0.01M, dried to constant weight and sieved. The soil fraction less than 0.200 mm (total soil) was used for ^{13}C and ^{14}C analyses. Charcoal samples were also collected for carbon isotope analysis. A detailed description of the chemical treatment for soil and charcoal samples can be found in Pessenda *et al.* (1996a; 1996b).

The ^{14}C analyses on total soil and charcoal samples were carried out at the Radiocarbon Laboratory, Centro de Energia Nuclear na Agricultura (CENA), following the standard procedure for liquid scintillation counting (Pessenda and Camargo, 1991). The ^{14}C on small samples of charcoal were carried out at the Isotrace laboratory of the University of Toronto, employing the AMS technique. Radiocarbon data are reported as percent carbon modern (pmc) and radiocarbon ages as years BP.

Plants representative of the modern vegetation were also collected at each of the study sites in an area equivalent to 1000 m². For ^{13}C analysis, the leaves were washed, dried and grounded to < 0.100 mm. The ^{13}C analysis on soil and plant samples were carried out at the Environmental Isotopes Laboratory, University of Waterloo, using a Carlo Erba Analyzer attached to an Optima mass spectrometer. ^{13}C data are expressed in δ (‰) units relative to the PDB standard.

Carbon contents of soil samples were performed at the Soil Chemistry Section, CENA, by combustion in a Carbon Autoanalyzer and by wet digestion method, and are reported as percentages.

Results and discussion

Soil properties

The grain-size analysis indicated that clays comprise between 20 and 34% of the shallow soil horizons and increase to 57% in the deeper part of the soils representative of the forest, forest-transition and cerrado. The site representatives of the cerradão show higher clay content, ranging from 53 to 78% at the shallow and deeper part of the soil, respectively (Gomes, 1995).

The carbon contents show the typical soil profiles of decreasing carbon content with depth, similar to results obtained from most Amazonian oxisols (Volkoff and Cerri, 1988). They range between 1.9 and 5% in the shallow soil horizons decreasing to a carbon content as low as 0.30% in the deeper soil horizons (Gomes, 1995). Higher carbon content, between 5% at the surface and 0.8% in the deeper part of the soil, is observed at the cerrado site. This pattern may be related to the presence of small charcoal remains observed along most of the soil profile at this site. Desjardins *et al.* (1996) working in forest-savannah ecotones on medium-texture oxisols in Roraima, in the northern part of the Amazon region, found significant differences in the total C content between both vegetation types. The lower C content of savannah compared to the forest soil was related to its lower clay content and smaller litter input. These findings support previous studies in tropical areas that indicate that soils under tropical forest generally have higher carbon content in their uppermost layers than soils under tropical savannah vegetation (Sanches *et al.*, 1982; Feller *et al.*, 1991). The results obtained in the present study transect did not show the same pattern. The cerradão soil presents the highest clay content in the entire profile, but lower C content in the uppermost layers (0–100 cm), compared with the soils under the cerrado and forest-transition sites. In the case of the cerrado site, this pattern may be related to the presence of small charcoal remains observed along most of the soil profile.

Carbon isotope data

The radiocarbon data presented in Figure 2 correspond mainly to total SOM, since no attempts were made to date the humin fraction using the conventional ^{14}C technique, because of its low content in the soils under investigation. The ^{14}C data with values between 130 and 109 pmc clearly show the influence of bomb ^{14}C in the upper 30 cm of the soil profiles. The penetration of bomb carbon is more pronounced in the forest-transition site. The oldest dates in the lower part of the soil profiles are in the order of 3500 years BP. Since SOM is a mixture of a recent and an old carbon pool, this age should correspond to the minimum age of the carbon present in these profiles. Different studies in soil seem to indicate that the finer fractions tend to concentrate the older more degraded carbon and the coarse soil fractions tend to represent the more recent vegetation (Boutton, 1996). The cerradão soil in this study, which is characterized by the highest clay content, shows a younger radiocarbon date than the soil under cerrado but an older age than the forest transition site at the 90–100-cm sampling interval.

The radiocarbon data obtained from charcoal samples at the cerrado and the cerradão sites provide a better estimate of the time represented in the soil profiles. These data show radiocarbon ages of 540 years and 5930 years at the sampling intervals 20–30 cm and 90–100 cm, respectively, at the cerrado site, and 2050 years and 7000 years was obtained at 60 cm and 150 cm in the cerradão soil. The shallow charcoal date correlates very well with the date obtained in the SOM. The deepest charcoal date is about 3500 years older than the SOM and it is likely that the charcoal date represents the maximum age of the carbon at 150 cm. This suggests that the ^{13}C record in the 200-cm soil profiles presented in this paper represents changes in the vegetation communities of perhaps as much as 8000 years. Soil age-depth profiles obtained on humin and charcoal samples in other study sites in Brazil (including two sites in the Amazon Basin) yield an age of about 9000 to 12 000 yr BP for the 200 cm soil horizon (Martinelli *et al.*, 1996; Pessenda *et al.*, 1996a; 1996b; 1997; 1998), broadly consistent with our estimates. A recent paper by Desjardins *et al.* (1996) reported charcoal radiocarbon dates in the range of 6540 and 7630 yr BP for savannah soil at the 62 and 78 cm soil horizons.

^{13}C data

The $\delta^{13}C$ values for SOM on the forest and forest transition regions range from −28.3‰ to −25.1‰ and −29.0‰ to −24.1‰, respectively (Figure 3). The ^{13}C enrichment with depth is probably due to decomposition of soil organic matter (Nadelhoffer and Fry, 1988; Heidmann and Scharpenseel, 1992). This isotopic pattern is typical for soil organic matter generated by C_3 vegetation type (Cerri *et al.*, 1985; Boutton, 1991; Pessenda *et al.*, 1996b). The forest transition profile shows a slight trend to more ^{13}C-enriched values at depth than the forest site and could indicate minor influence of C_4 plants, as suggested by Desjardins *et al.* (1996). These results indicate, however, that the C_3 vegetation type has been predominant in the regions represented by the forest transition site, Pimenta Bueno (central-southern region of Rondonia state) and the forest site, Ariquemes (northern region of Rondonia state), during the time represented by this record.

A wider range of $\delta^{13}C$ values between −30‰ and −14‰ is observed at the soil sites representative of cerradão and cerrado vegetation communities (Figure 3). The $\delta^{13}C$ depth profile for the cerradão site shows a ^{13}C trend ranging from −30‰ and −25‰ in the deepest part of the profile (150–200 cm), increasing to about −18.8‰ between 30 and 90 cm and then reversing towards more ^{13}C-depleted values (−27.5‰ and −25.1‰) at the surface (0–20 cm). This trend suggests a predominance of C_3 vegetation in the lower part of the record that should represent the early Holocene, changing to a vegetation community consisting predominantly of C_4 plants, recorded in the interval between 120 and 30 cm (middle and late Holocene), then returning to a predominance of C_3 plants in the interval 30 cm at the surface (recent).

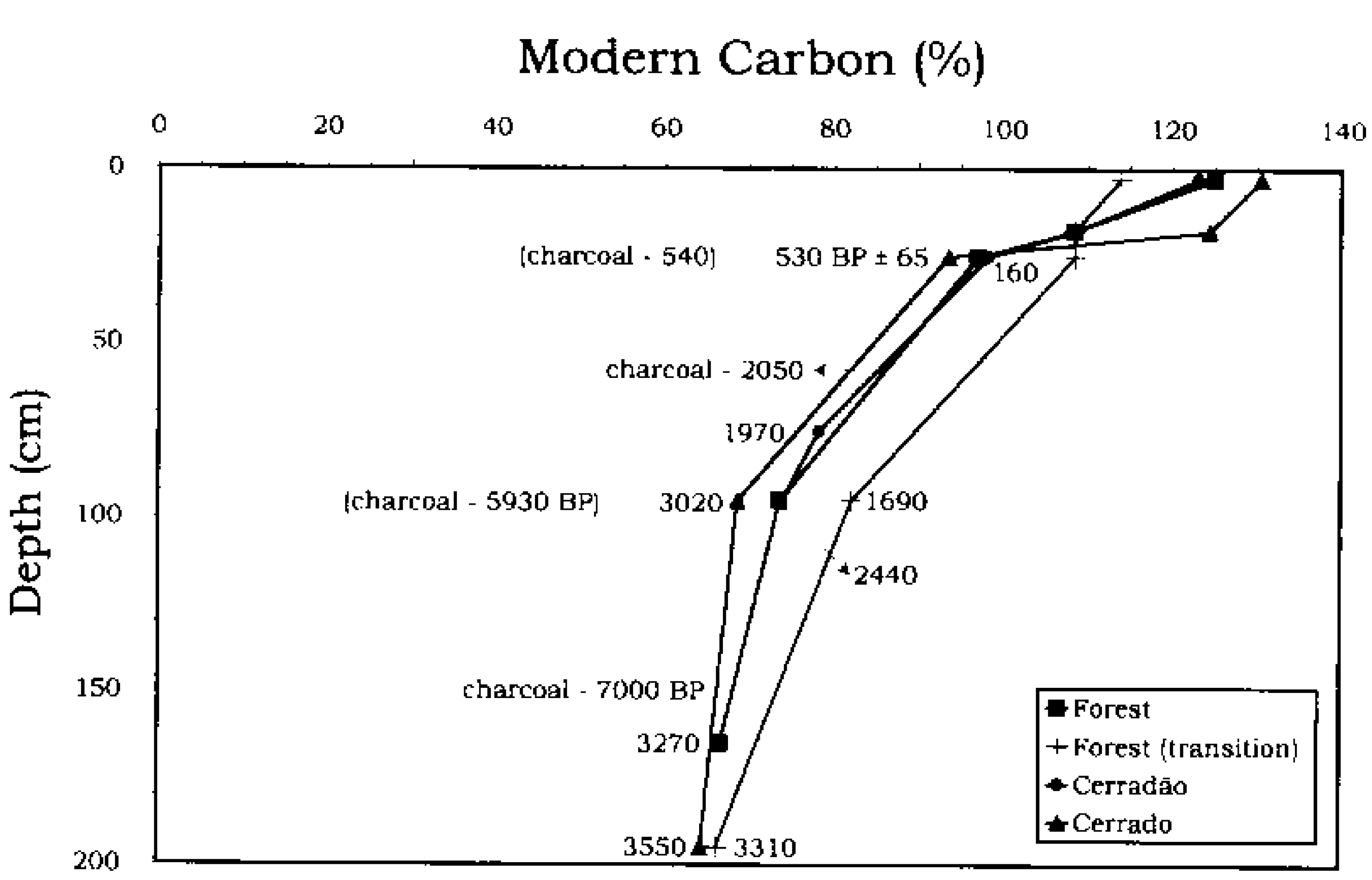

Figure 2 Radiocarbon dating of total SOM and charcoal samples.

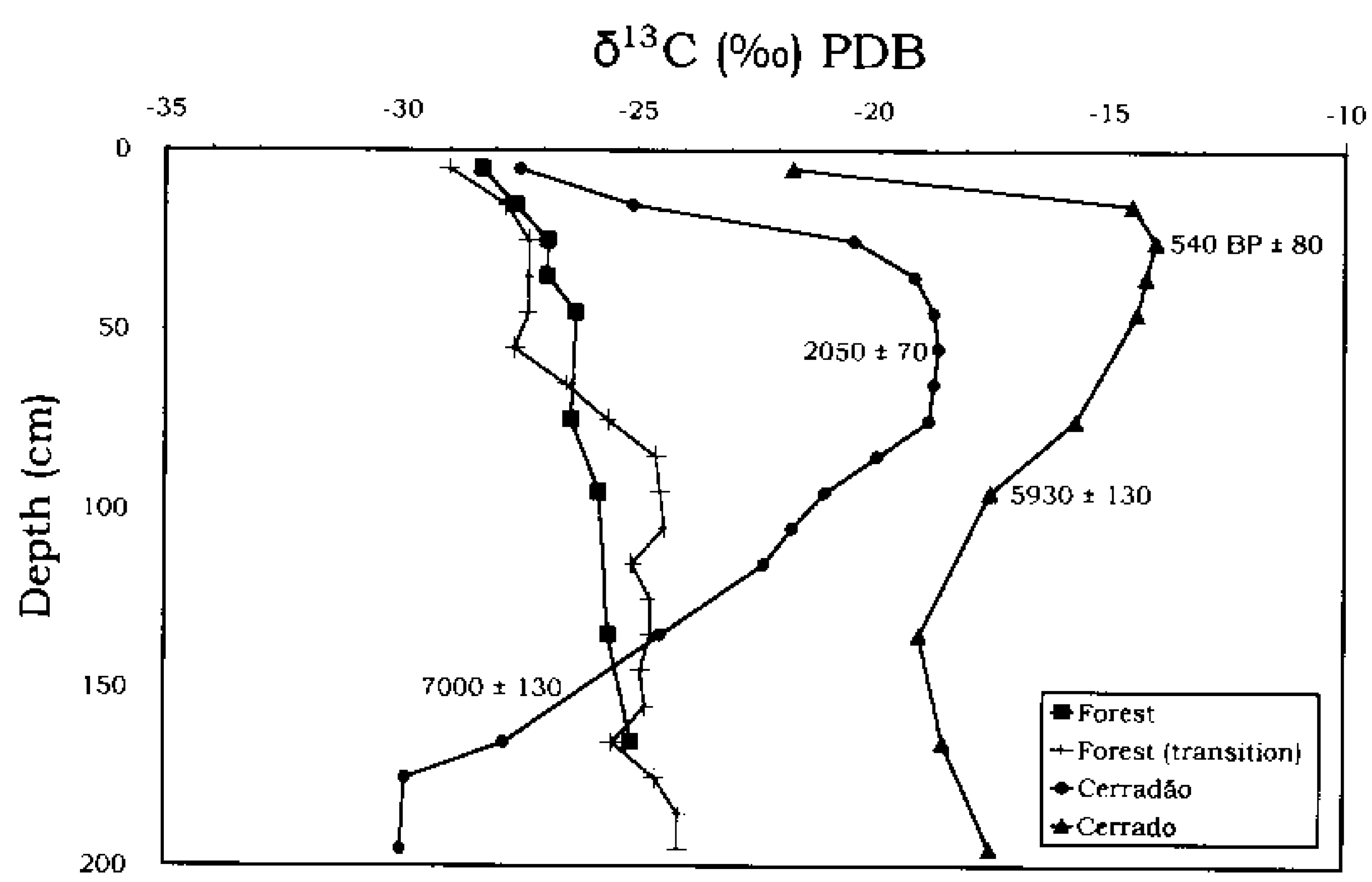

Figure 3 Natural variation of $\delta^{13}C$ in relation to soil depth.

Similar $\delta^{13}C$ profiles have been reported by Schwartz *et al.* (1986) in Africa and Desjardins *et al.* (1991; 1996) and Pessenda *et al.* (1997; 1998) in Brazil, implying a change from a C_3 to C_4 to C_3 vegetation type.

The most negative $\delta^{13}C$ value (−30‰) observed at the interval 170–200 cm probably suggests the presence of a very dense forest in the present cerradão during the early Holocene. $\delta^{13}C$ data obtained on modern plants collected in a forest-savannah transect in the Humaita region, northern Rondonia state, clearly show a relationship between highest forest density and more negative $\delta^{13}C$ values. A detailed study of the composition of modern vegetation at the cerradão site and $\delta^{13}C$ data show that about 96% of the identified vegetation are C_3 plants (Gomes, 1995). $\delta^{13}C$ values for the modern vegetation range between −36.7‰ to −28.6‰, with a mean $\delta^{13}C$ value of −31.9‰. An orchid species (family Orchidaceae) with a ^{13}C of −19.2‰ appears to be part of the CAM plant type. No ^{13}C values typical of C_4 plants were measured at this site.

A comparison of the information inferred from the ^{13}C data obtained in the soil profile and the composition of the modern vegetation at the cerradão site, implying that there was a change in the vegetation community in the past, characterized by the existence of C_4 plants that are not represented in the modern community.

The $\delta^{13}C$ record at the cerrado site seems to show a similar pattern, but much more ^{13}C-enriched values than at the cerradão site (Figure 3). The $\delta^{13}C$ values range from −17.5 to −19.0‰, in the depth interval 90–200 cm, increasing to more positive values −14.8 to −15.7‰ at 10–80 cm and reversing towards more negative $\delta^{13}C$ values (−21.7‰) at the surface layer (0–10 cm). This site clearly show the influence of C_4 plants during most of the time represented at this site. Palynological and palaeolimnological studies in central Brazil and eastern Amazon have shown that savannahs appeared with the development of a drier climate, beginning 8000 yr BP and reaching a maximum at 6000–5000 yr BP (Absy *et al.*, 1991; Ledru, 1993). The existence of charcoal samples dated between 7000 and 6000 yr BP in the cerradão and cerrado soils, probably derived from palaeofires that occurred during the dry period, supports the interpretation that the present savannah appeared during the mid-Holocene.

A survey of modern vegetation and $\delta^{13}C$ data indicated that about 80% of the identified vegetation of the cerrado communities are C_3 plants, and 20% are composed of C_4 plants (Gomes, 1995). The ^{13}C data show values between −26.9 and −31.7‰ for the C_3 plants with a mean of −29±1.8‰. The C_4 plants range between −11.1 and −13.0‰, with a mean value of −11.7±0.7‰. A comparison of these data with the soil $\delta^{13}C$ profile suggests that C_4 plants were much more abundant in the past than today in the cerrado.

The $\delta^{13}C$ pattern in soil organic matter and inferred vegetation changes reported in this study have also been reported in other transitional regions between forest and savannah of the Amazon region (Desjardins *et al.*, 1996; Pessenda *et al.*, 1997; 1998; Sanaiotti, 1996) suggesting regional scale changes in vegetation communities occurred in the Amazon Basin during the Holocene. The regional dimension represented by the cerrado and the cerradão sites separated by 200 km also supports the hypothesis that large areas of the Amazon region have been affected by vegetation changes.

Conclusions

The $\delta^{13}C$ data collected in soils along the transect Vilhena to Ariquemes in the Rondonia region clearly indicate that the vegetation communities in the areas represented by the forest and the forest transition sites have not changed significantly during the time represented in the soil profiles. In contrast, significant changes in plant communities are observed in the cerradão and cerrado ecosystems. Both soil profiles at these sites show that C_4 plants were an important component of the terrestrial vegetation during the mid-Holocene at the cerradão site and during the early to the beginning of the late Holocene at the cerrado site. The early part of the record shows a major influence of C_3 plants that is clearly documented at the cerradão site. The $\delta^{13}C$ pattern observed in the soil profiles collectively indicates an expansion of the forest during the early Holocene, an expansion of the savannah during the Middle Holocene and a more recent forest expansion during the late Holocene. Our results are consistent with several studies that have documented the expansion of the tropical forest in the south tropical zone of south America between 10 000–9500 and 8000 yr BP (Absy *et al.*, 1991; Van der Hammen, 1991; Servant *et al.*, 1993), and in the Humaita region, south of Amazon state (Pessenda *et al.*, 1997; 1998). Dry periods during 20 000–13 000 and 8000–4000 years BP in areas close to and in the Amazon region have also been documented (e.g., Servant and Fontes, 1978; Wirrmann *et al.*, 1988; Absy *et al.*, 1991; Ybert, 1992; Desjardins *et al.*, 1996; Pessenda *et al.*, 1997; 1998). The data presented in this paper add to mounting evidence of forest-savannah boundary fluctuations in the southern Brazilian Amazon during the Holocene.

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