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CARBON DYNAMICS IN VERTISOLS AS REVEALED BY HIGH-RESOLUTION SAMPLING

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ABSTRACT. Two Vertisol soil profiles under xeric soil moisture regimes, located at Qedma and Akko, Israel, were investigated and compared to a profile under ustic moisture regime, located in Hyderabad, India. Samples were taken in complete successive 2 cm thin layers down to about 180 cm depth or more. Organic and inorganic carbon were analyzed with regard to ^{13}C and ^{14}C concentrations. While all soils have radiocarbon ages of several thousand years BP, the depth distributions reveal substantial differences between the soil carbon dynamics. ^{14}C and, less pronounced, δ^{13}C clearly reflect the pedoturbation process. Further, its strength is found to be related to mainly soil moisture regime, then clay content and land use. In one soil, a change of growing from C_4 to C_3 crops in the past can be concluded from the δ^{13}C depth distribution.

INTRODUCTION

Vertisols are soils mostly derived from alluvium or basic rocks. They are characterized by a clay content of >30%, uniformly to a depth of at least 50 cm (Soil Survey Staff 1998), typically even 1 m or more (FAO 1998). Smectites, mostly montmorillonite, provide ≥80% of the clay, whereby more than 50% of the soil organic carbon is associated with the clay fractions. Also typical is a high amount of nutrients. Because of these characteristics, the soil is plastic and sticky when wet, and develops cracks of up to 5 cm in diameter down to about 1.5 m depth during periods of drying. These physical properties make Vertisols difficult for agricultural use without heavy input of energy and/or irrigation. Therefore, tillage is usually done at the beginning of the rainy season.

The succession of dry and rainy seasons through the year leads to periodically shrinking and swelling of the soil with the development of patterns of deep cracks (Yaalon and Kalmar 1978). This process, also commonly called "self mulching", is still not completely understood. When, at the beginning of the rainy season, surface soil material is falling into the cracks, the swelling results in strong forces in lateral and later on also in upward direction. At the site of Akko, Yaalon and Kalmar (1972) measured a resulting upward surface movement of 50 mm yr^{-1} resp. 0.2–0.5 mm d^{-1}. Characteristic evidence for this pedoturbation are stress cutanes ("slickensides") found on aggregate surfaces below the zone of the cracks which are formed by the shear forces. Under certain circumstances, pedoturbation in Vertisols also leads to lateral inhomogeneity with elevated and depressed areas, a micro-relief called Gilgai after an Australian aborigines term (Blackburn et al. 1979; Kovda et al. 2001). In the soils studied here, however, no Gilgai phenomenon was observed.

The pedoturbation should result in a mixture of material of different depths down to the end of the cracks in the bottom soil. In our study we wanted to find answers to the questions of whether and how this mixing is reflected in the depth distribution of soil organic carbon as well as ^{14}C age and δ^{13}C. Further, we wanted to examine a relation between soil moisture, clay mineral content, and vegetation respective to land use and the strength of mixing.

In the past, most radiocarbon dates of Vertisols, like of other soil orders, have been gained from samples taken out of different depths or horizons where representativeness was just assumed. This is a questionable method however, especially when only small samples sufficient for dating by AMS

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were taken, because the homogeneity is disturbed by pedoturbation. Therefore, we sampled a complete soil monolith divided into thin horizontal slices.

Vertisols cover 3.16 million km^2 (about 2.4%) of the ice-free land surface of the world and are found mainly in temperate and tropical areas, but also under boreal climate. More than half of the Vertisol area has an ustic soil moisture regime, two thirds of this occurring in the tropics. The second-most distributed is the aridic soil moisture regime frequently occurring on the desert fringes (Dudal and Eswaran 1988; Eswaran et al. 1999). The continent with the largest total area of Vertisols, mostly Torrerts, is Australia, while the largest contiguous areas of Vertisols under ustic soil moisture regime are the Gezira in Sudan and the Deccan plateau in India.

For our study we chose three representative Vertisol soils, one from the Deccan plateau in India, which is under ustic soil moisture regime, and two soils under xeric soil moisture regime from Israel, one in the south and one in the north. The ustic soil moisture regime is characterized by the rainy season being during summer and fall, whereas summer and fall under the Xeric moisture regime are dry. The Israelian soils differ from each other by clay content and total annual precipitation.

Soils

Following are the sites and soil profile descriptions of the soils. The horizon designation is according to Soil Taxonomy (Soil Survey Staff 1990).

Profile Qedma (Israel) 31°41′N, 34°47′E

- *Classification*: Calcic Vertisol (FAO), Typic Pelloxerert (USDA), Grumusol (Local)
- *Climate*: semiarid, 19 °C average air temperature, 11 °C in January, 25 °C in August, 465 mm annual precipitation, soil moist December to May.
- *Land use/vegetation*: cultivated for many centuries, no remnants of natural vegetation, since about 1880 under cotton (irrigated), since around 1975 fallow (cement mining pit)
- *Clay content*: about 53% (Agassi et al. 1985), cracks found mostly to 50 cm, few to 100–112 cm
- *Sampled in*: February 1986 by Peter Becker-Heidmann, Hans-Wilhelm Scharpenseel, and Dan Yaalon, measured 1987/1988

Depth (cm)	Horizon	Description
0–8	A11	Heavy clay, very dark greyish brown (10YR 3/2)
8–26	A12	Heavy clay, very dark greyish brown (10YR 3/2)
26–56	B1	Dry and heavy clay, carbonate nodules at 52–56 cm
56–112	B21	Heavy clay, very dark greyish brown (10YR 3/2), many well expressed slickensides, polyeder, Mn concretions
112–140	B22	Heavy clay, very dark greyish brown (10YR 3/2), many slickensides
140–250	B23	Slickensides, carbonate nodules at 250 cm
250–750	C	Bedrock
750–900	Cca	Calcic horizon, bedrock

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Profile Akko (Western Galilee Experimental Farm, Israel) 32°54'N, 35°15'E

- *Classification*: Typic Pelloxerert (USDA), Grumusol (Local)
- *Climate*: subhumid to Mediterranean, 19 °C average air temperature, 11 °C in January, 25 °C in August, 626 mm annual precipitation with maximum (150 mm) in January, soil moist October to May.
- *Land use/vegetation*: no information about very early times available, probably swamp area, since about 1880 drained, fallow (Orni and Yaalon 1966)
- *Clay content*: >67%, mostly montmorillonite, cracks found mostly down to 40 cm, few to 100 cm
- *Sampled in*: 1985 by Dov Kalmar and Dan Yaalon, measured 1986/1987

Depth (cm)	Horizon	Description
0–15	A	Heavy clay, very dark greyish brown (10YR 3/2), very small carbonate nodules, many fine and medium roots
15–40	B1	Heavy clay, very dark greyish brown (10YR 3/2), very small carbonate nodules, many fine roots, soft boundary transitions
40–100	B21	Heavy clay, very dark greyish brown (10YR 3/2), very small carbonate nodules, many slickensides, very few fine roots, texture: polyeder
100–140	B22	Heavy clay, very dark greyish brown (10YR 3/2), very small carbonate nodules, many well expressed slickensides, very few fine roots
140–187+	B23	Heavy clay, very dark greyish brown (10YR 3/2), some carbonate nodules, many slickensides, no roots

Profile Patancheru (India) 17°35′N, 78°17′E

- *Classification*: Pellic Vertisol (FAO), Typic Pellustert (USDA), Kasireddipalli Series (Local)
- *Climate*: semiarid, 26 °C average air temperature, maximum in August, 760 mm annual precipitation with 80% between June and September, soil moist June to October
- *Land use/vegetation*: very old low input farming, since 1972 research farm (ICRISAT) growing sorghum, pulses, safflower
- *Clay content*: 65% smectites
- *Sampled during*: the dry season, November 1983, by Peter Becker-Heidmann, measured 1988/1989

Depth (cm)	Horizon	Description
0–20	Ap	Very dark grayish brown (10YR 3/2), common roots, lime
20–40	A12	Very dark grayish brown (10YR 3/2), common roots, lime
40–60	A13	Very dark gray (10YR 3/1), very few roots, lime concretions
60–90	A14	Very dark gray (10YR 3/1), very few roots, lime concretions
90–130	AC	Very dark gray (10YR 3/1), dark-brown (10YR 3/3) mottles
130–180+	C	Yellowish to olive brown (2.5Y 5/4), basaltic alluvium

METHODS

The soil samples were taken as successive 2 cm thin complete layers from an area of about 1 m^2, down to at least 180 cm depth. Details are described in Becker-Heidmann and Scharpenseel (1986). Before shipping to the laboratory, the samples were air dried, in India also ground. In the laboratory roots and stones were removed. Each sample was dispersed with distilled water and carefully homogenized by stirring, followed by sieving to 2 mm and drying at 105 °C. The carbon content was conductometrically determined using a Wösthoff apparatus. Organic and inorganic carbon were separated by combustion temperature in a pure oxygen stream. To obtain the correct separation temperature, a CO_2 release vs. temperature diagram was recorded for at least one representative sample of each horizon, showing a plateau above the combustion temperature of the organic fraction and below carbonate destruction. The separation temperature was set in the middle of this plateau. To cross check this method, these samples were also treated with 4% hydrochloric acid and the $\delta^{13}C$ values compared. For further details see Andresen (1987).

The CO_2 from carbonate in the soils studied here was set free above a temperature of 600–700 °C only. The organic fraction was combusted totally at 550 °C and the CO_2 trapped. The combustion residue then was heated to 1000 °C to get the carbonate fraction. Benzene preparation and measurement by liquid scintillation counting as well as preparation and measurement of $\delta^{13}C$ was conducted as described in detail by Becker-Heidmann (1989).

RESULTS AND DISCUSSION

The high-resolution depth distribution curves of carbon content, conventional ^{14}C age and $\delta^{13}C$ of the organic and inorganic fractions are shown in Figures 1–9. For the exact data cf. Tables 9–11 in the Hamburg Radiocarbon Thin Layer Soil Data Base (Becker-Heidmann et al. 1996), which was published as contribution to the International Radiocarbon Soils Data Bank (IRSDB) being in development (Becker-Heidmann 1996).

Carbon Content

The contents and depth distributions of organic and inorganic carbon of the three soil profiles are substantially different. The Qedma profile (Figure 1) has the lowest organic carbon content, nearly constant throughout the whole depth, and at the same time, the highest carbonate content. In the upper 100 cm or so, the inorganic carbon content is nearly constant, i.e. very slightly increasing with depth, and distinctively decreasing with depth only below about 100 cm. Correspondingly, we found many cracks in the upper 100 cm and no cracks below.

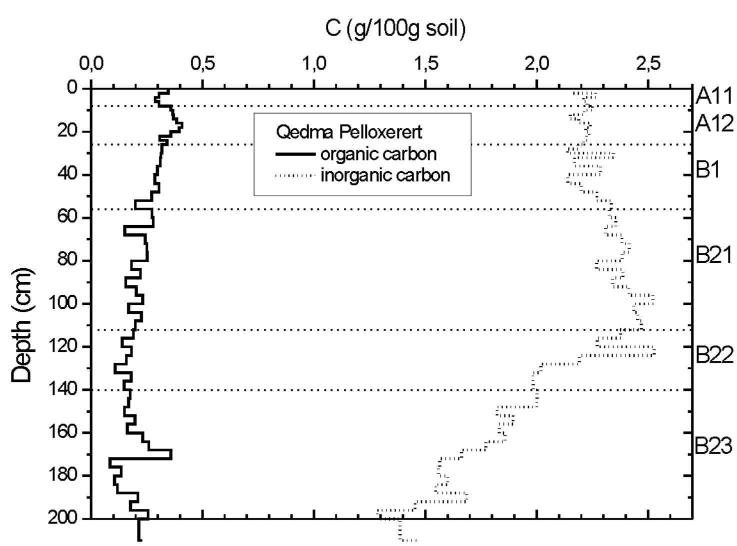

Figure 1 Organic and inorganic carbon, Qedma profile

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The depth distribution of organic carbon in the Akko profile (Figure 4) differs from the other two, showing a pseudo-exponential decrease with depth like in undisturbed forest soils.

The organic carbon in the Patancheru profile (Figure 7) is uniform within the A and C horizons and decreases from 0.5 to 0.15 in the transition horizon between A horizon and basic rock (C).

Radiocarbon Age

We are aware of the fact that soil organic matter is an open system for which the basic assumption underlying the "age" concept is not strictly valid. The alternative use of terms like "apparent mean residence time" or "minimum age" has been discussed controversially in detail without generally applicable results (cf. Scharpenseel and Becker-Heidmann 1992). Therefore, the most honest way of presenting ^{14}C measurements is surely just as activities. In this study we are mainly interested in comparing ^{14}C data of different depths and between different profiles. Only because the time periods and differences are important in this context, we use here, as a more intuitive representation of the ^{14}C data, the "conventional radiocarbon age" as defined in Stuiver and Polach (1977) without interpreting them as ages.

More clearly than by the carbon content, pedoturbation is indicated by the depth distribution of conventional ^{14}C age within the zone of cracks. Generally, an increase of ^{14}C age with depth is characteristic for almost all soils. In the Vertisol at Qedma however, a distinct increase is apparent only below about 100 cm and is small above, for the organic as well as the inorganic fraction (Figure 2). The material especially in the B21 horizon between 60 and 100 cm is some thousand years younger than one would expect from extrapolating the age depth trend occurring in the deeper part of the profile. Rejuvenation by recent carbon falling into the cracks is a plausible explanation. The remarkably large differences of ^{14}C ages between adjacent layers within 130 and 180 cm probably result from fluctuating maximum depth of swelling and shrinking in years with different soil moisture. In the surface layers, due to the weaker yawing forces, aggregates are not as much destroyed as in the deeper soil. Therefore, homogenization is incomplete, resulting in the observed large differences in ^{14}C age between successive sampled layers.

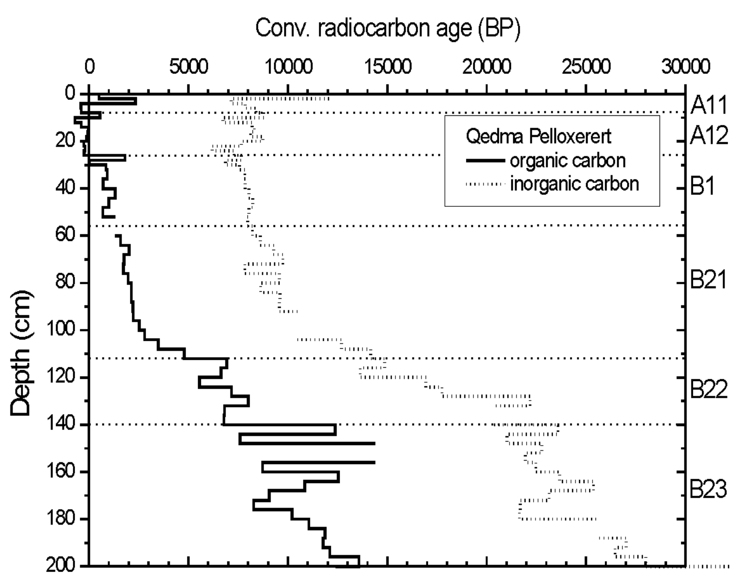

Figure 2 ^{14}C age of organic and inorganic carbon, Qedma profile

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The ^{14}C age of organic and inorganic carbon show nearly parallel depth distributions, with the inorganic fraction being older by 7000 BP down to about 100 cm and 10,000 BP below. This is probably the result of isotopic exchange between the organic and inorganic soil carbon fractions: Primary (marine) carbonates originate from times long before soil development and contain no or only very little ^{14}C. We expect, therefore, to find the same old ^{14}C age in all depths for this carbonates in the absence of any interaction. The effects of isotopic exchange on the ^{14}C age of interacting soil carbon fractions were discussed in general by Becker-Heidmann (1989), distinguishing two cases: a one-time reaction and a continuous exchange. In the case of repeated exchange between two fractions, both fractions can gain a range of resulting ages between the two initial ages.

As distinguished from this, in the single exchange model between a ^{14}C-containing and a ^{14}C-free carbon fraction the ^{14}C age of the ^{14}C-containing fraction increases by a constant value, which depends only on the amount of exchange, for example, 1 half-life in case of exchanging 50%, while the former ^{14}C-free fraction gets a ^{14}C age being higher than that of the ^{14}C-containing by a constant amount. The parallel curves of organic and inorganic carbon thus clearly indicate that such a single exchange had happened and that the fractional amount of exchange was the same for the whole profile. As most of the humus in Vertisols is water insoluble and bound to the clay mineral phase, it seems likely that only during the short primary decomposition of organic input, in a micro-environment of low pH produced by fulvic acids and root elucidates, CO_2 from decomposition and carbonates meet in the intermediate carbonic acid phase.

The increase of ^{14}C age with depth is less in the Akko profile (Figure 5) than at Qedma with organic carbon reaching only 7000 BP at 180 cm depth. A change of the gradient at the maximum depth of cracks can be seen only for the inorganic carbon. The depth distribution of the inorganic carbon follows the organic with a difference of about +3000 BP down to 140 cm, below with up to +6000 BP. If pedoturbation is responsible for the only small increase of ^{14}C age with depth, this process is more pronounced in this soil than in the Qedma profile. Additionally, the closer values of organic and inorganic carbon indicate a more intensive contact and a larger isotopic exchange.

In the Patancheru profile the organic carbon has nearly the same ^{14}C age through all depths (Figure 8). Especially striking is the unusual high age of 3000 BP within the Ap horizon already. The carbonate ^{14}C age is even closer to the organic carbon than at Akko and starts to increase stronger below the maximum depth of cracks at 90 cm. We might conclude, therefore, that of the three studied profiles pedoturbation is the strongest here. The variations of ^{14}C age with some extreme deviations at several small depth intervals indicate that the material is transported by pedoturbation partly in nearly undisturbed small aggregates.

Stable Carbon Isotope

The depth distributions of $\delta^{13}C$ generally support the interpretation drawn from the ^{14}C age curves. In the Qedma profile, however, the trend of strong increase of $\delta^{13}C$ of organic carbon with depth down to 140 cm not only contradicts pedoturbation (Figure 3). The difference between the values between −24 and −21‰ in the A horizons and about −15‰ at maximum depth of cracks is much higher than the approximately 3‰ we usually find in soils under natural vegetation and interpret as result of soil processes as decomposition and isotope discrimination by transport and fixation (Becker-Heidmann 1989). The $\delta^{13}C$ value of −15‰ PDB is a clear indication of a former C_4 type vegetation, while the last grown C_3 crop (cotton) dominates in the organic matter of the A horizons. The observed large variations of $\delta^{13}C$ between successive layers within the zone of cracks are puzzling. Possibly the roots of the C_3 plants preferred the existing cracks for faster reaching the groundwater building fine roots mainly near the horizon borders where water percolation is usually slightly inhibited (Becker-Heidmann 1989). The organic matter resulting from decomposition of these fine roots would, in the case of low pedoturbation, mostly remain where it was produced. Contrary to the organic carbon, the $\delta^{13}C$ value of the inorganic carbon is approximately 9‰ PDB with nearly no change with depth. A close interaction with the organic carbon as seen in the other profiles and related to the pedoturbation process can therefore be excluded.

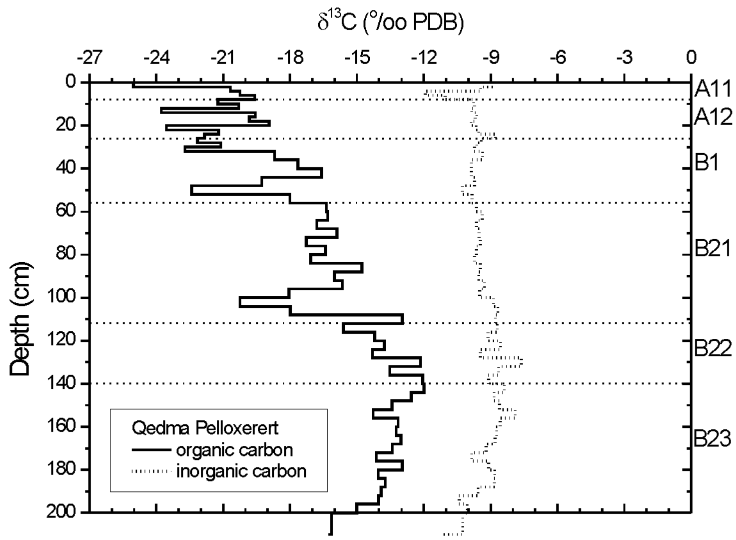

Figure 3 $\delta^{13}C$ of organic and inorganic carbon, Qedma profile

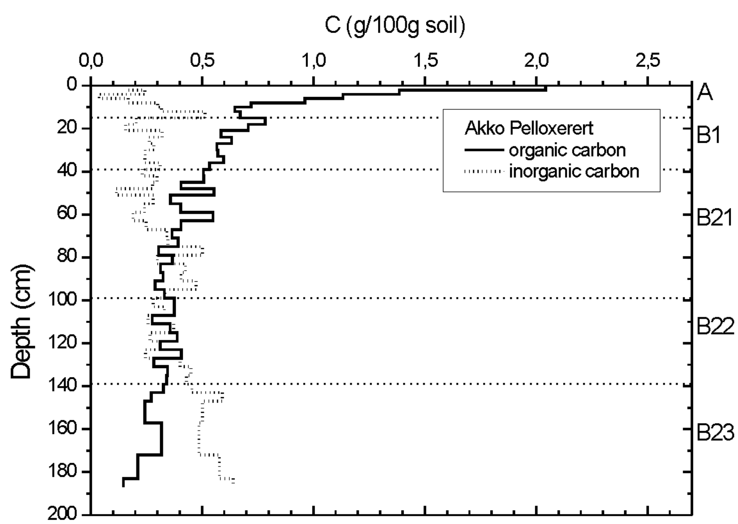

Figure 4 Organic and inorganic carbon, Akko profile

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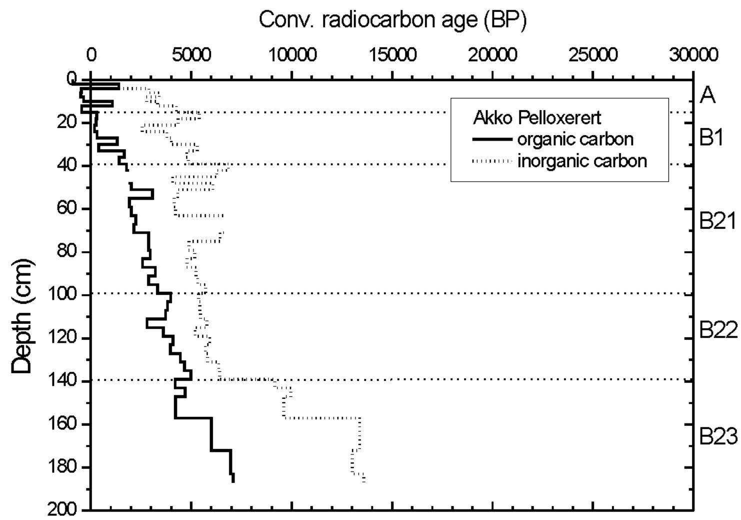

Figure 5 ^{14}C age of organic and inorganic carbon, Akko profile

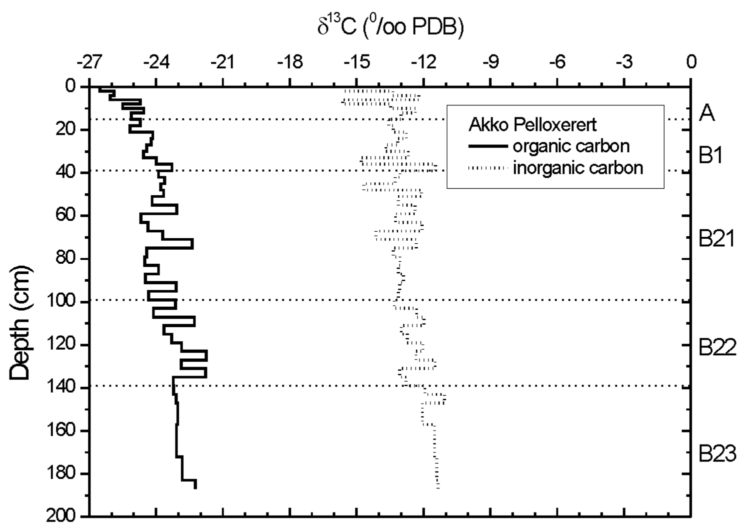

Figure 6 $\delta^{13}C$ of organic and inorganic carbon, Akko profile

In the Akko profile $\delta^{13}C$ of organic carbon is increasing with depth in the A horizon by only about 2‰, from −26.5‰ PDB typical for C_3 plants (Figure 6). Below to the maximum depth of cracks there is nearly no more change, below 100 cm then again a slight increase can be seen. The depth distribution strictly follows these gradients. Together, these results confirm the pedoturbation process in this profile concluded from the ^{14}C age curve.

The $\delta^{13}C$ depth distributions of organic and inorganic carbon in the Patancheru profile (Figure 9) are very similar to those of Akko and, therefore, also confirm the pedoturbation. The value of −15‰ PDB of the organic carbon however relates to a C_4 vegetation (sorghum), and its lower variation through depth indicates a stronger mixing of the soil.

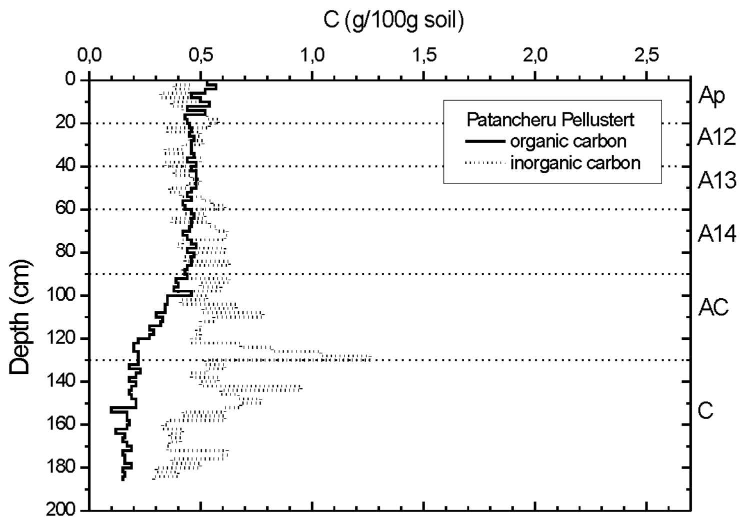

Figure 7 Organic and inorganic carbon, Patancheru profile

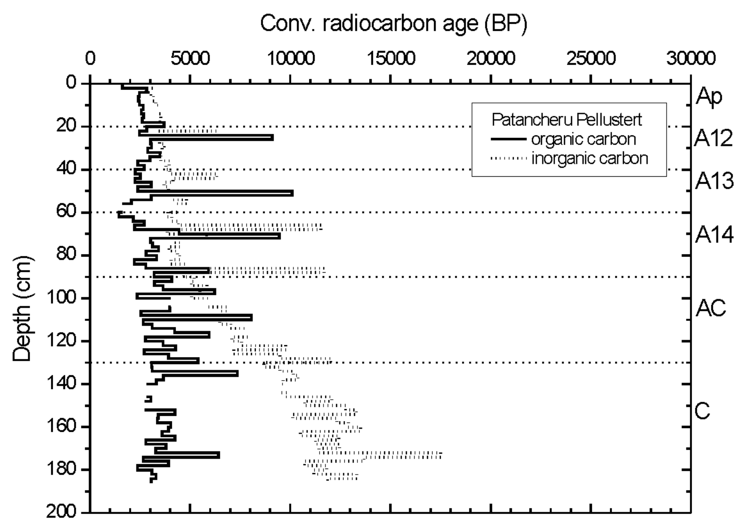

Figure 8 ^{14}C age of organic and inorganic carbon, Patancheru profile

Comparison to Other Studies

From the different depth curves of the ^{14}C age of organic matter as well as carbonate within the three studied Vertisols, the intensity of pedoturbation can be estimated. A very low increase of the ^{14}C age with depth means a strong pedoturbation. Scharpenseel et al. (1984) studied Sudanese Vertisols from the Gezira in comparison to other countries, and Scharpenseel et al. (1986) compiled 378 ^{14}C ages of horizon-wise sampled Vertisols from all over the world, limited to a sampling depth of 200 cm including the zone of cracking. They calculated linear regression curves for the data sets country by country. The results for the country data with the highest and the lowest increase of age by depth are listed in Table 1, together with those obtained for the three soil profiles of this study.

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The ^{14}C age gradient of the Qedma profile corresponds to the highest reported (for Bulgaria), while Patancheru shows even stronger pedoturbation by a lower ^{14}C age increase with depth than the one found for the Sudanese Vertisols. If we account for the depth distribution discontinuity at 100 cm in the Qedma profile (Figure 2) and assume that pedoturbation is actually limited to the upper 100 cm, the linear regression for this profile part than gives a lower ^{14}C age gradient. A possible explanation could be that the soil had been irrigated during the period of cotton growing in the past, enhancing pedoturbation within the rooting depth. The influence of the C_3 plant seen in the $\delta^{13}C$ depth distribution also reaches down to this depth and thereby supports this hypothesis.

Table 1 Linear regression coefficients of ^{14}C age depth distributions of organic carbon in the studied soil profiles compared to data from Scharpenseel et al. (1984, 1986)

		Regression equation: ^{14}C age = A + B • depth	
Location	Depth (cm)	A (yr BP)	B (yr BP/cm)
Qedma	0–200	−1337.7	64.78
	0–100	−153.6	26.94
	100–200	−277.1	60.40
Akko		−136.4	36.65
Patancheru		3112.9	4.44
Bulgaria		−1735.3	63.01
Sudan		−2387.3	8.22

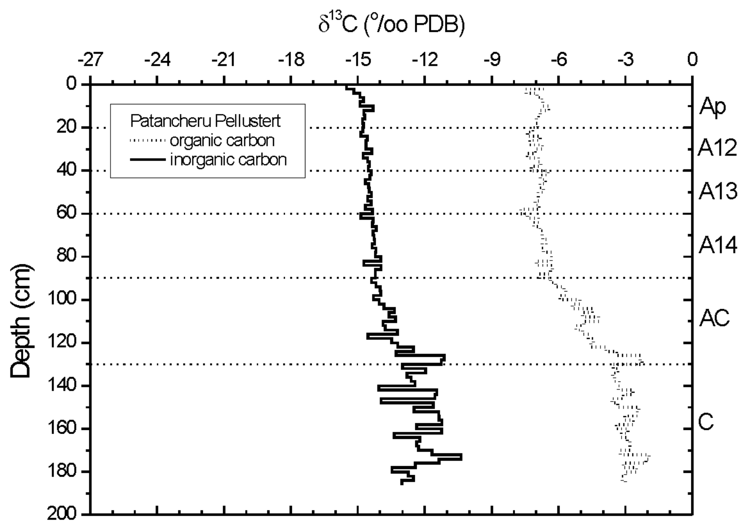

Figure 9 $\delta^{13}C$ of organic and inorganic carbon, Patancheru profile

CONCLUSION

The effect of pedoturbation is clearly reflected in the ^{14}C age, better than in the organic carbon content: there is little or no increase in age with depth within the zone of cracks. As a measure of the strength of mixture the closeness of the ^{14}C age curves of organic and inorganic carbon due to isotope exchange can also be used. The $\delta^{13}C$ depth distribution generally confirms the interpretation of the ^{14}C age curves related to pedoturbation. The strength of mixing is correlated mainly to soil moisture, i.e. more expressed in soils with ustic than with xeric moisture regime. The second important factor is the smectite content which increases in the order Qedma—Akko—Patancheru. Also, land use may have an impact as the soil permanently under crops shows stronger pedoturbation than the fallow ones. Additionally, the $\delta^{13}C$ depth distribution of Qedma reveals former growing of C_4 plants. The high-resolution depth profiles obtained by thin layer soil sampling clearly reveal whether the soil aggregates are disturbed and homogenized during pedoturbation.

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