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With regards.
Partha Sarathi

Palaeoclimate and palaeovegetation in central India during the Upper Cretaceous based on stable isotope composition of the palaeosol carbonates

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Abstract

The oxygen isotope compositions of the pedogenic carbonates formed on the sediments of the Lameta Formation of Central India during the Upper Cretaceous range from -6.7 to -8.9‰ . Estimates of the oxygen isotope composition of the soil-water in equilibrium with the carbonates suggest average meteoric water composition of -8‰ . This value is considerably lighter compared to the modern precipitation in Central India (-3‰). The lighter oxygen isotope composition can be explained in terms of cumulative effects of highly seasonal (monsoon-like) climatic regime in a rain shadow zone and a more pronounced “continental effect” due to a bigger size of Cretaceous India.

The carbon isotopic compositions of the Lameta carbonates range from -7.1 to -10.7 with an average of -9.1‰ suggesting pedogenesis in soils dominated by C_3 type of vegetation. The estimated average composition of the vegetation is about 3‰ enriched compared to the modern day C_3 vegetation. This is probably due to atmospheric influence contributing about 15% of the total CO_2 in the soil. An analysis of this contribution using the model of Cerling (1991) indicates that the partial pressure of CO_2 in the Late Cretaceous atmosphere was $800\text{--}12,000$ ppmV.

1. Introduction

Recent advances in the field of isotope geochemistry have demonstrated that the oxygen and carbon isotope compositions of palaeosol carbonates (commonly referred to as caliche or calcrete) are useful palaeoclimatic and palaeobiologic indicators. The oxygen and carbon atoms constituting the pedogenic carbonates ($CaCO_3$) are derived from soil-water and soil- CO_2 , respectively. Therefore, the isotopic compositions of oxygen and carbon in pedogenic carbonates reflect the compositions of these two sources.

The isotopic composition of oxygen in soil-water is determined chiefly by that of the meteoric water infiltrating the soil which, in turn, is controlled by

a number of meteorological and orogenic parameters like amount and seasonality of the rainfall, latitude and elevation of the station and its distance from the coast etc. (Rozanski et al., 1992). On the other hand, the isotopic composition of carbon in the soil- CO_2 at a given depth is controlled by the composition of the plant derived CO_2 , the depth in soil profile, difference in the pressures of soil- CO_2 and atmospheric CO_2 etc. (Cerling, 1984). The composition of the soil- CO_2 and its pressure are related to the nature and volume of vegetation and their seasonal activity (Cerling, 1984, 1991; Mack et al., 1991; Cerling et al., 1989; Salomons et al., 1978; Salomons and Mook, 1976; Dever, 1983).

In Central India around the city of Jabalpur

(Lat. $23^{\circ}10'N$, Long. $80^{\circ}E$) a sequence of calcareous sediments of Upper Cretaceous age known as Lameta Formation (sensu Ghosh and Rudra, 1993) is exposed (Fig. 1; cf. Pascoe, 1964; Brookfield and Sahni, 1987; Tandon et al., 1990). The fluvial sediments of the Lameta Formation transitionally overlies fluvial sandstones and mudstones of Cretaceous Jabalpur Formation and is conformably overlain by Tertiary Deccan Trap basalts (without any significant evidence of contact metamorphic alterations). A number of calcic palaeosols (Fig. 2), stacked vertically, have been recorded in the Lameta Formation. It has been noted that the development of the calcic palaeosols took place in alternation with the fluvial depositional events. These vertically stacked palaeosols

are excellently preserved due to the protective capping by the Deccan basalts. In this study the pedogenic carbonates of the Lameta Formation have been analyzed for oxygen and carbon isotopic compositions to infer the palaeoclimatic and palaeovegetational setup of the Central India during the Uppermost Cretaceous time.

The information obtained from the stable isotopic analysis of the Lameta pedogenic carbonates can be used to test the existing models of the Cretaceous climate in the context of the on going debate about it (Barron, 1983; Hallam, 1984). This study may also help in understanding the climatic setup under which the global mass-extinction at the Cretaceous–Tertiary boundary took place.

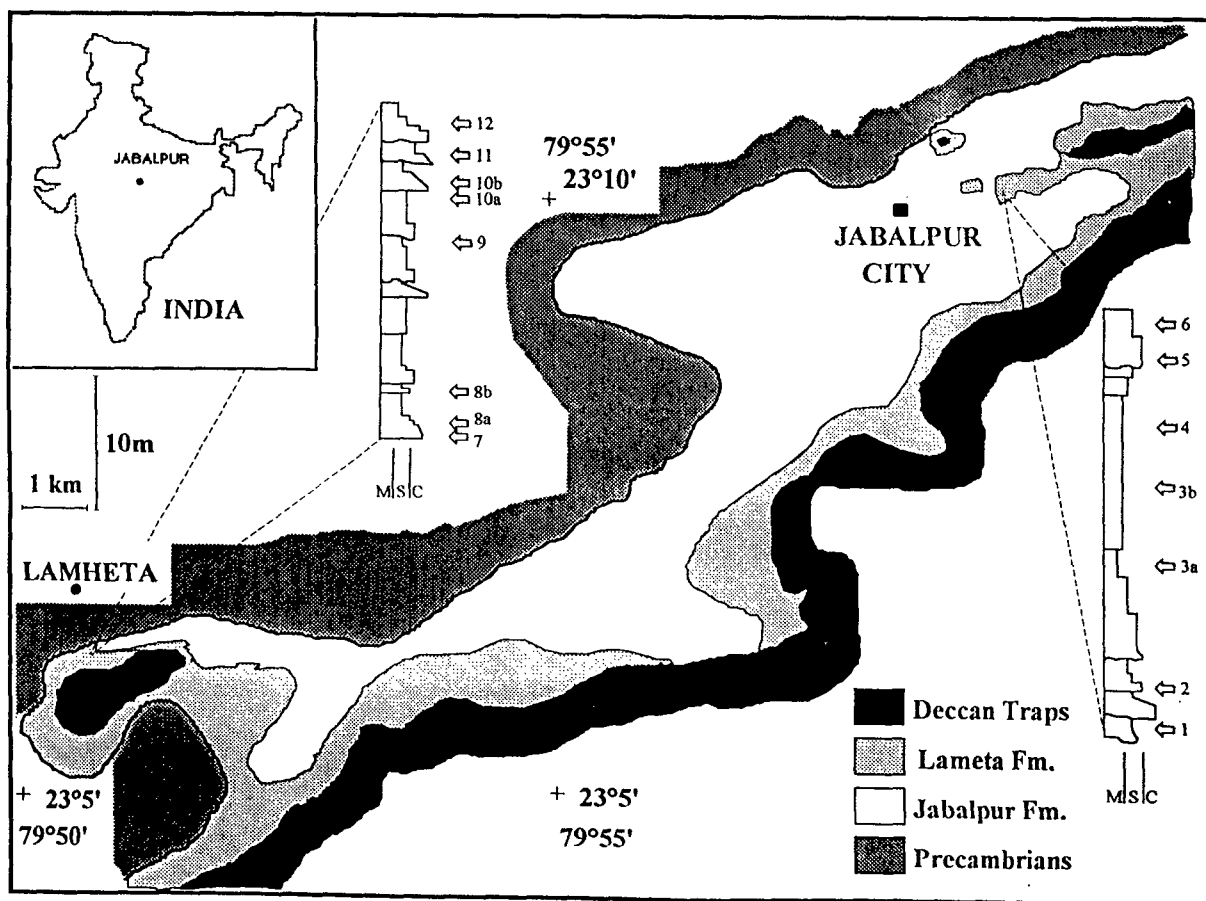


Fig. 1. Geological map of the area around Jabalpur. Sample positions are indicated in the lithologies of the Lameta Formation, one near the Lamheta village and the other near the Jabalpur City (Sample positions of the Kuropani village are not shown).

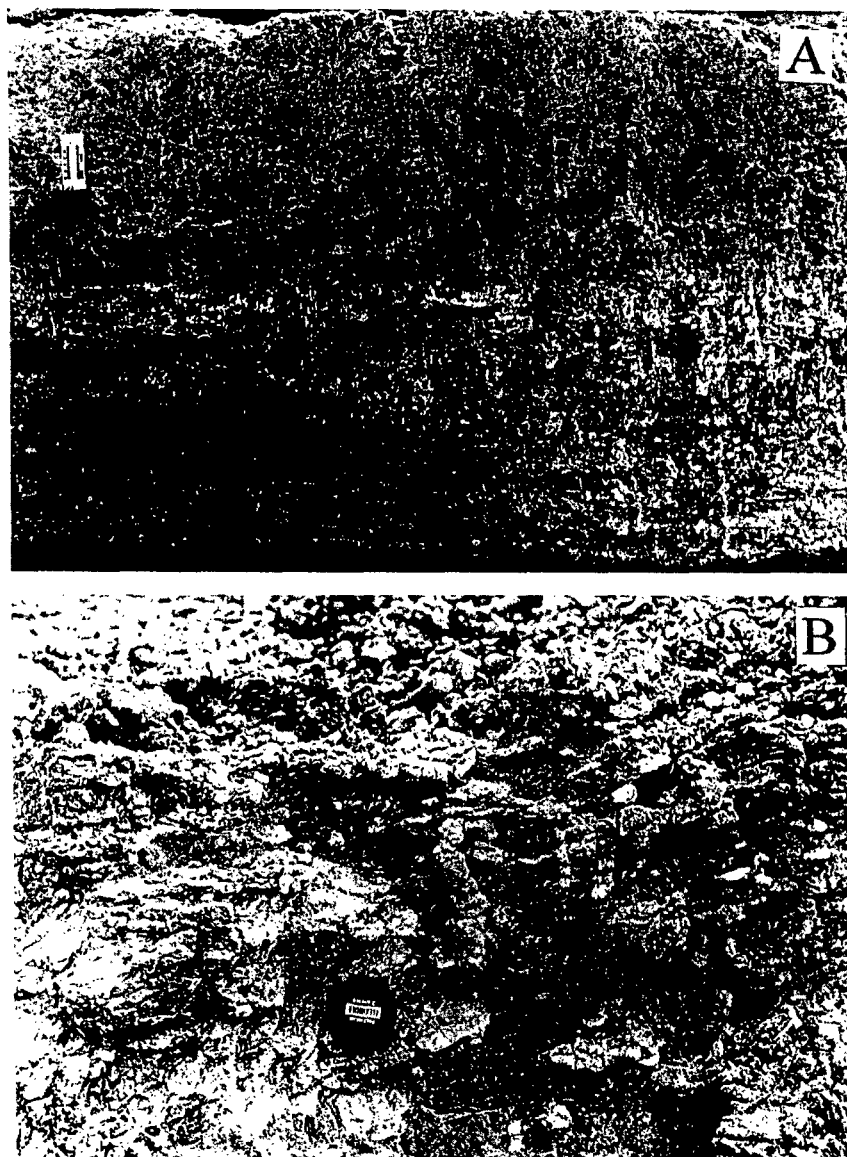


Fig. 2. Calcic palaeosol profiles. A. Soil developed in the channel-fill sandstones of the Lameta Formation. Note the increase in intensity of calcification upwards, the vertically oriented rhizocretions and development of hardpan horizon near the top. Scale bar equals 10 cm. Location: 1.5 km SE of Lamheta village. B. Soil developed in the fine grained floodplain sediments of the Lameta Formation. Note (1) the profuse development of pedogenic glaebules towards the top, (2) a well developed rhizocretion in the center. Diameter of the measuring tape case is 5 cm. Location: 2 km E of the Jabalpur City.

2. Lithologic description

The Lameta Formation (sensu. Ghosh and Rudra, 1993) around Jabalpur comprises ≈ 35 m thick sequence of calcretised fluvial sediments

(Fig. 1). Conspicuous continental fossils like dinosaur bones and egg shells, fresh water molluscs, ostracods have been reported from the formation (Tandon et al., 1990). The Lameta Formation mainly comprises of an association of tabular and

lenticular channel-fill bodies of coarse calcareous sandstones (light gray—N8) and conglomerate interspaced with floodplain deposits of calcareous clayey fine sands (grayish yellow—5 Y 8/3 to red purple—10 RP 2/2; often blotchy). The calcareous nature of the sandstones of the Lameta Formation is not a primary depositional feature but was imparted later by pedogenic calcareous cementation. The calcareous sandy sediments are composed of subrounded to subangular detrital quartz and pebble to coarse sand sized pedogenic calcareous nodules of varying shapes. The micritic–microsparry–sparry cement in these sandstones is ubiquitous, but in certain instances may occupy as much as 60% of the total volume resulting in a

floating grain fabric (Fig. 3A). The pedogenically modified sediments show features like micritic envelopes around detrital grains, spar-filled branching root channels, irregular clots of micrite within a groundmass of microsars, alveolar texture etc. (Fig. 3) indicating calcification in active vadose zone by pedogenic processes. In the conglomerates intraformational caliche derived clasts comprise about 75% of the framework grains and extrabasinal jasper, quartz, chert fragments constitute the rest.

Though the shape of the Lameta sandbodies and their large-scale architectural elements are clearly discernible, the internal primary structures, excepting a few faint traces of cross-beds, are not

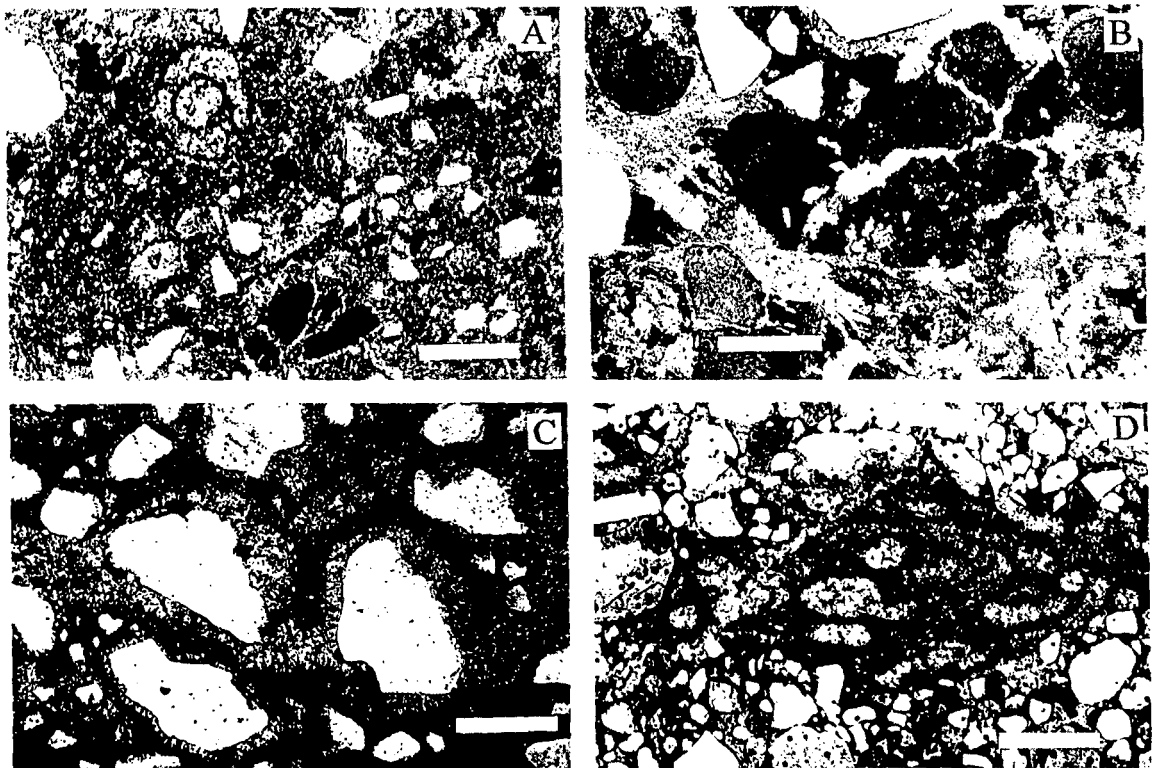


Fig. 3. Photomicrograph showing some micro morphological features typical of the Lameta calcic palaeosols. A. Sandy limestone in Lameta Formation (under crossed polars). Note (1): the detrital quartz grains floating in a micritic groundmass, (2): transverse section of a spar-filled root channel in the upper left part of the photograph. Scale bar = 366 μm . B. Calcareous glauabule in coarse grained channel-fill sediments of the Lameta Formation (under crossed polars). Note the explosion of the glauabule by displacive calcitization. Scale bar = 270 μm . C. Dark micritic envelopes around the detrital quartz grains (plane polarized light). Note the corrosion of the quartz grain boundaries by calcite. Scale bar = 290 μm . D. Development of alveolar texture (under crossed polars) in the left central part of the photograph. note the spar-filled bean shaped alveoli within the elliptical body. Crossed polars. Scale bar = 697 μm .

clearly visible mainly because of pedogenic modification. The sediments are generally massive. The Lameta sandbodies are however, characterised by a number of vertically stacked FU sequences, each having erosive base marked by conglomeratic material.

In field the calcareous Lameta sediments show well developed pedogenic features like, very coarse sand to pebble sized subspherical to platy glaeboles, tubular tapering and branching down calcareous root molds, subhorizontal mats formed of small interwoven calcareous root molds, irregular subhorizontal fractures etc. (Fig. 2). The pedogenic features demarcate distinct pedo horizons comparable to the nodular caliche of Esteban and Klappa (1983) or modern-day Bk soil horizon (Soil Survey Staff, 1975) and caliche hardpans or petrocalcic horizons (K soil horizon). In general, the gleyed horizons and the horizons similar to the argillic or structural B are very rare in the Lameta sequence.

The palaeosol horizons of the Lameta Formation are organized in thin ordered vertical sequences constituting palaeosol profiles. The palaeosol profiles, individually constituted of a sequence of 2–3 types of pedohorizons, are 50 cm to 2 m thick and on average can be traced laterally for about 5 m or so. A large number of palaeosol profiles (max. 10) stacked one upon the other can be encountered in a single vertical traverse through the Lameta sequence. Stacking of compound, composite and cumulate profiles of both the truncated and untruncated types (*sensu* Marriot and Wright, 1993) can be noted. The sequence of truncated profiles is common in the channel-fill bodies whereas the cumulate and composite profile sequences are common in the floodplain deposits.

In the Lameta palaeosol profiles the nodular horizons (calcic B) are volumetrically most significant, which often grades up to highly calcified platy or petrocalcic (K) horizons and are usually underlain by rhizcretion zones (Fig. 2A). In very rare instances, thin argillic or structural B horizons are developed on top of the petrocalcic horizons. A comparison between the present day soils and the calcic palaeosols of the Lameta Formation suggest that the latter are quite similar to the aridzone soils (aridisols; Soil Survey Staff, 1975).

3. The stable isotopic composition

3.1. Sampling and analytical methods

A total of 19 samples of calcareous sandstones were collected from three localities: Jabalpur city, Lamheta village and Kuropani village (located 100 km ENE of Jabalpur, see Fig. 1 for the first two locations). In all the localities sampling was done from three stratigraphic levels, named Lower Limestone, Mottled Nodular Bed and Upper Limestone (Matley, 1921). Each level per locality was sampled more than once (where possible) so that some samples comprise mainly pedogenic micrite while the other is dominated by sparry calcite. This was done in order to distinguish the stable isotopic composition of pedogenic material from any possible non pedogenic overprinting. All the samples were taken from either Bk or K soil horizons and consist of caliche nodules (glaeboles) and tubular rhizcretions. The gleyed soils were avoided in order to sample soils of high free-air porosity (Cerling, 1991). Effort was made to ensure that the samples were collected at least 25 cm below the top of the soil profiles in order to exclude any possible surficial alteration due to exchange with atmosphere (Cerling, 1984). We have also analysed a calcareous nodule developed in the recent sediments of the Narmada River.

Stable isotopic measurements were carried out on hand picked slices of the rocks (after examination through petrographic microscope to determine the amount of spar and micrite present in it). After powdering, the samples were reacted with 100% orthophosphoric acid (Sarkar et al., 1990) in vacuo at 50°C. The evolved CO₂ gas was thoroughly cleaned of water vapor and was analyzed in a VG Micromass 602D mass spectrometer. The isotopic ratios of carbon and oxygen are presented in standard δ -notation (‰) in PDB scale (Table 1). Reproducibility of the analyses was $\pm 0.1\%$ for both the carbon and oxygen isotopes.

3.2. Results and discussion

The $\delta^{13}\text{C}$ values of the samples from the Lameta Formation have a mean of -9.1% and standard

Table 1

Isotopic data of the Lameta associated pedogenic carbonates and a recent concretion along with derived composition of meteoric water and associated vegetation

Location	Sample no. (Code)	$\delta^{13}\text{C}(\text{‰})^*$	$\delta^{18}\text{O}(\text{‰})$	$\delta^{18}\text{O}$ of soil water (‰) [†]	$\delta^{18}\text{O}$ of meteoric water (‰) [†]	$\delta^{13}\text{C}$ of soil CO_2 (‰) [†]	Estimated $\delta^{13}\text{C}$ of plant CO_2 (‰) [†]	
Jabalpur City (Bara Simla)	1 (203)/LLP)	-9.6	-8.2	-6.2	-8.2	-19.3	-23.7	
	2 (204)/LL/G)	-8.6	-7.4	-5.4	-7.4	-18.3	-22.7	
	3a (RHIZ/MMB/P)	-8.7	-5.7**	-3.7	-5.7**	-18.4	-22.8	
	3b (RHIZ/MNB/P2)	-6.6	-6.7	-4.7	-6.7	-16.3	-20.7	
	4 (390)/M/P)	-10.1	-8.3	-6.3	-8.3	-19.8	-24.2	
	5 (252)/UL/P)	-9.0	-7.3	-5.3	-7.3	-18.7	-23.1	
Lamheta village	6 (357)/UL/P)	-7.1	-10.5**	-8.5	-10.5**	-16.8	-21.2	
	7 (357)UL/P)	-9.3	-8.5	-6.5	-8.5	-19.0	-23.4	
	8a (215)/LL/G)	-9.6	-8.9	-6.9	-8.9	-19.3	-23.7	
	8b (SILC/M/P)	-9.6	-8.8	-6.8	-8.8	-19.3	-23.7	
	9 (166)/M/P)	-10.1	-8.1	-6.1	-8.1	-19.8	-24.2	
	10a (RHIZ/UL/P)	-8.9	-8.0	-6.0	-8.0	-18.6	-23.0	
	10b (ROOT/UL/P)	-8.6	-7.6	-5.6	-7.6	-18.3	-22.7	
	11 (379)/UL/P)	-9.7	-7.8	-5.8	-7.8	-19.4	-23.8	
	12 (162)/UL/G)	-8.1	-8.4	-6.4	-8.4	-17.8	-22.2	
	Kuropani village	13 (332)/LL/P)	-9.1	-8.2	-6.2	-8.2	-18.8	-23.2
		14 (327)/LL/P)	-9.2	-8.0	-6.0	-8.0	-18.9	-23.3
15 (329)/M/P)		-9.8	-7.0	-5.0	-7.0	-19.5	-23.9	
Narmada river bank	16 (330)/UL/P)	-10.7	-8.6	-6.6	-8.6	-20.4	-24.8	
	17 (Recent concretion)	-3.8	-2.9	-0.9	-2.9	-13.5	-18.3	

*The values are w.r.t. PDB with 1σ errors $\pm 0.1\%$ on both carbon and oxygen isotope ratios.

[†]These values are calculated assuming soil water in equilibrium with soil carbonate and soil CO_2 at 25°C . $\delta^{18}\text{O}$ values are w.r.t. SMOW and $\delta^{13}\text{C}$ w.r.t. PDB.

**These are considered as outliers.

deviation of 1‰ . The corresponding mean value of $\delta^{18}\text{O}$ is -8‰ and standard deviation 1‰ . The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are plotted in a correlation diagram in Fig. 4 which shows that except two outliers the values are closely clustered around a $\delta^{18}\text{O}$ value of -8‰ and a $\delta^{13}\text{C}$ value of -9‰ .

In order to derive palaeoclimatic information from the stable isotopic composition of the palaeosol carbonates it is necessary to establish that the samples have not undergone significant alterations subsequent to their formation. This can be substantiated by the following arguments.

Firstly, the dominance of pedogenic micrites and their fabric (discussed before) in the samples indicate that these carbonates have undergone

minimal recrystallization and were formed in active vadose zone.

Secondly, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for the two types of samples, one having dominance of spars and the other dominance of pedogenic micrites form overlapping clusters (see Fig. 4); this suggests that the recrystallization of pedogenic micrites into spars, if any, did not alter the isotopic compositions of the carbonates significantly; this is similar to the finding of Cerling (1984).

Finally, the presence of low ^{18}O and ^{13}C contents in the carbonates indicate little or no diagenetic modifications. For example the recent concretion from this area have isotopic composition of -3.8‰ ($\delta^{13}\text{C}$) and -2.9‰ ($\delta^{18}\text{O}$), distinctly

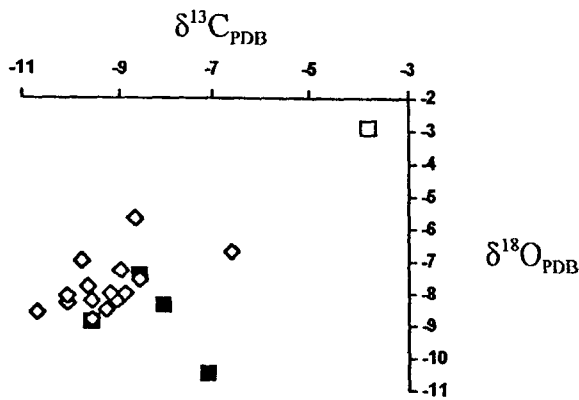
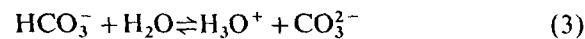
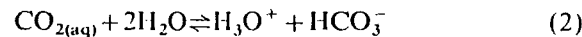


Fig. 4. Plot of the $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ values of the 19 pedogenic carbonate samples from the Lameta Formation and 1 recent concretion (open square) from the study area. Open diamonds represents samples rich in pedogenic micrite and filled squares sparry calcite.

higher than those of the palaeosols. This observation suggests a minimal alteration by groundwaters, at least in recent times.

3.3. Conditions of CaCO_3 precipitation

The percolating surface waters carrying the required ions precipitate calcium carbonate in the soil under favourable physico-chemical conditions. The chemical reactions involved in this process are as follows:



Each of the above reactions is accompanied by fractionation of oxygen and carbon isotopes which are controlled either by kinetic effects or by equilibrium exchange. Since the pedogenic carbonate formation is very slow in nature most of the precipitation can be assumed to take place under equilibrium conditions.

The equilibrium exchange fractionation is temperature dependent. The temperature coefficient of oxygen isotope fractionation between carbonate and water is about $+0.24\text{‰}$ per $^\circ\text{C}$, (Craig, 1965), while that of carbon isotope fractionation between

carbonate and dissolved bicarbonate is about -0.10‰ per $^\circ\text{C}$ (Lesniak and Sakai, 1989). So in order to derive the isotopic composition of O of soil-water and C of soil- CO_2 from the isotopic compositions of O and C in pedogenic CaCO_3 , the temperature of calcium carbonate precipitation needs to be estimated independently.

The predominant calcic nature of the Lameta palaeosols indicate a warm climatic regime (Birkeland, 1984). Though the accumulation and retention of calcium carbonate in soils is governed by aridity as well as by temperature, calcic soils are more common in hot and arid climatic regions than in cold and arid regions. This is mainly due to the higher evapotranspiration in hot climate compared to cold climate. For the accumulation of carbonate in soil the potential evapotranspiration needs to be higher than the mean annual precipitation, otherwise leaching of CaCO_3 can occur (Cerling, pers. comm., 1994). Moreover, abundant root molds in the Lameta palaeosols indicate presence of significant vegetation which could not be possibly sustained in a cold and arid climate.

Some idea about the surface temperature can also be obtained from the palaeogeographic reconstruction of the Indian continent which suggests that the study area was located around 20°S latitude during the Cretaceous (Dietz and Holden, 1970). In the contemporary climatic scenario the areas occurring in that latitudinal belt have mean annual temperature around 25°C (Kolars and Nystuen, 1975). Additionally, in one of the simulations of Cretaceous climate, Barron and Washington (1982) obtained a mean annual temperature of about 27°C for India during the Mid Cretaceous. An arid and hot palaeoclimatic set up for the central part of India during the Late Cretaceous have also been suggested in the reconstruction of Parrish et al. (1982). Though the present pattern of global isotherms may be different from what they were during the Cretaceous, the mean annual temperature of this region is not expected to be very different from 25°C and further discussion will assume this value.

3.4. Oxygen isotopic composition

The $\delta^{18}\text{O}$ values of water in equilibrium with carbonate at 25°C are calculated using the well

known relations summarized by Friedman and O'Neil (1977) and show (Table 1) that the expected oxygen isotopic composition of the soil-water in equilibrium with the Lameta carbonates formed at 25°C ranges from -4.7‰ to -6.9‰ SMOW (excluding the two outliers: -3.7 and -8.5‰).

3.5. Connection between the soil-water and meteoric water

The composition of soil-water associated with the Lameta pedogenic carbonates can be used to derive the local meteoric water composition if the effect of evaporation is taken into account. Salomons et al. (1978) have shown earlier that the composition of calcretes from western India is about 3‰ enriched compared to the expected value based on present day meteoric water composition. However, they assumed a mean rainfall composition of -6‰ which is 1‰ lighter than the observed composition in their sampling localities (see Bhattacharya et al., 1985, and fig. 21 of Yurtsever and Gat, 1981). Therefore, instead of 3‰ enrichment a more appropriate value would be $\approx 2\text{‰}$. The 2‰ enrichment is also estimated from a comparison of calculated recent soil-water composition (-0.9‰) based on a recent concretion (Table 1) and the present day rainfall of about -3‰ in the study area (op. cit.). A similar enrichment presumably operated during the Cretaceous times since the nature of the climate and mean annual temperature at that time were similar to that of today.

Therefore, to derive the meteoric water composition one has to subtract 2‰ from the δ -value of the soil-water (see Table 1). The Lameta soil-water composition of -4.7 to -6.9‰ would thus correspond to meteoric water composition of -6.7 to -8.9‰ with a mean of $\approx -8\text{‰}$. Therefore, the isotopic composition of the Cretaceous meteoric water of Central India is lighter by about 5‰ compared to the δ -value of the present day meteoric waters.

3.6. Implication of lighter meteoric water in Cretaceous India

The composition of the meteoric water at a given place is determined by the source water

composition and various meteorological processes affecting isotopic composition by Rayleigh fractionation (Rozanski et al., 1992). It is now generally accepted that the Cretaceous sea was lighter in oxygen isotopic composition by about 1‰ (Shackleton and Kennett, 1975). Since the sea surface temperature in the equatorial belt was similar (Barron and Washington, 1982), it can be assumed that the atmospheric moisture was also equally depleted in the equatorial region. This leaves a net depletion of 4‰ to be explained by atmospheric "Rayleigh processes".

Depletion in isotopic composition of meteoric waters can occur due to increase in rainfall amount. The I.A.E.A. compilation of isotopic values of rainwaters in tropical stations (Rozanski et al., 1992) shows that an increase of 250 mm rainfall can approximately account for a decrease of 4‰ in $\delta^{18}\text{O}$. The present day rainfall in the study area is about 1200 mm (Rao, 1976) and predominantly takes place during the SW monsoon (June to September). Therefore, an increase of 250 mm rainfall would imply a total rainfall of about 1450 mm over Cretaceous central India. However, such high rainfall distributed uniformly over the whole year is incompatible with the field character of the palaeosol profiles which lack thick well differentiated argillic and cambic horizons and are dominated by calcic horizons occurring at the top of the profiles. Therefore, the rainfall was probably highly seasonal (monsoon-like) and could at best be somewhat more intense compared to the present day amount. Thus an "amount effect" can probably explain only a part of the 4‰ depletion in isotopic composition.

Present-day Indian groundwaters show a negative correlation between their $\delta^{18}\text{O}$ values and the distance of the sampling localities from the coast where the moisture bearing winds enter the continent (Bhattacharya et al., 1985). This phenomenon called "continental effect" is caused by successive "rainouts" from the wind system as it progresses inside the continent leaving the moisture in the wind increasingly lighter. During the Cretaceous period, the Indian continent was located in the southern hemisphere centering around 20°S and probably experienced a monsoon-like northwesterly wind system carrying moisture from the equa-

torial Tethys sea (Barron and Washington, 1982; Parrish et al., 1982; Parrish and Peterson, 1988). Assuming a similar magnitude of “continental effect” as of today i.e. 4‰ decrease for 1000 km (Bhattacharya et al., 1985) a net fractionation of –7‰ can be explained by a distance of about 1750 km from “Central India” towards the coast in northwestern direction. This distance is larger by about 400 km than the distance to Jabalpur from the base of the mountain range in northwest India. Therefore, a bigger size of continental India needs to be envisaged if the entire depletion is to be explained by the “continental effect”. The magnitude of the required increase in size, of course, reduces in proportion to the extent of depletion to be explained by this process. It is of interest to note that Vecvers et al. (1975) proposed a similar magnitude of size reduction in the northwestern margin of India after its collision with the Asian landmass.

Part of the depletion could also have been caused if this area was located in a rain shadow zone as the heavier isotopes of oxygen would have preferentially rained out on the wind-ward side. The study area is presently flanked by the highlands of southeast and northwest India (Vindhyan and Bundelkhand regions) which were significantly higher in Cretaceous time and could have presented efficient orographic barriers.

Above discussion suggests that the relatively lower $\delta^{18}\text{O}$ value of –8‰ of Cretaceous meteoric water over Central India probably reflects the combined influence of palaeogeographic and palaeoclimatic effects.

3.7. Carbon isotopic composition

The carbon in soil carbonate is predominantly derived from the CO_2 available in the soil called “soil- CO_2 ” (sensu Mack et al., 1991). Therefore, the $\delta^{13}\text{C}$ value of the soil- CO_2 can be derived from that of the soil carbonate using equilibrium exchange relation between CO_2 and calcite (Deines et al., 1974). The soil- CO_2 is an admixture of atmospheric and non-atmospheric CO_2 components. The CO_2 derived from the plants forms the bulk of non-atmospheric CO_2 , while bacterial fermentation (Irwin et al., 1977; Mack et al., 1991)

may contribute a part in some cases. However, the latter requires anaerobic reducing environment, which is unlikely in the case of aridisols accumulating CaCO_3 in the porous, well aerated fluvial sediment of Lameta Formation. Moreover, bacterial fermentation or methanogenesis contributes isotopically heavy carbon (upto +15‰) to the CO_2 and the resultant carbonates (Irwin et al., 1977). In the Lameta samples no $\delta^{13}\text{C}$ value heavier than –6.6‰ have been observed and hence any significant input of CO_2 by bacterial fermentation is unlikely. Moreover, the zone of bacterial fermentation lies typically below 10 m depth which far exceeds the profile thicknesses of the Lameta palaeosols.

Hence, the Lameta soil- CO_2 can be considered as an admixture of plant derived CO_2 and atmospheric CO_2 components. Cerling (1991) has shown that the carbon isotopic composition of the soil- CO_2 (and soil carbonate in equilibrium with the soil- CO_2) is essentially constant below 20 cm depth. The Lameta carbonate samples were collected from at least 25 cm below the top of the soil profiles and therefore, should faithfully reflect the composition of CO_2 derived from the existing vegetation.

The isotopic composition of plant- CO_2 is dependent on the proportion of different types of vegetation since the $\delta^{13}\text{C}$ values of the plants are determined by the photosynthetic pathways (Cerling, 1991; Mack et al., 1991). Mainly three types of pathways are important. The majority of the continental plants (i.e. virtually all trees, shrubs and herbs, and grasses favoured by a cool growing season) use C_3 or Calvin cycle. The $\delta^{13}\text{C}$ values of these plants range from –20 to –35‰, having an average of –27‰ (Ehleringer, 1989). The plants using C_4 or Hatch-Slack cycle include grasses favoured by warm growing seasons and a few shrubs in the families Euphorbiaceae and Chenopodiaceae. They average –13‰ but display a range between –6 and –19‰ (Smith and Epstein, 1971). The plants having CAM or Crassulacean Acid Metabolism cycle, include succulents like cactus and some yuccas; they show a natural range of $\delta^{13}\text{C}$ from –10‰ to –20‰ (Lerman, 1972).

However, a slight correction is required for the

above values when referring to the Cretaceous era, since the pre-industrial value of atmospheric CO₂ was about -6.5‰ compared to the modern day value of -8‰ (Friedli et al., 1986). In pre-industrial conditions the average isotopic compositions of C₃ and C₄ plants should have been ≈ -26 and -12‰ , respectively. This is confirmed by the fact that the fossil organic matters from most Mesozoic terrestrial plants have mean $\delta^{13}\text{C}$ value of about -26‰ (Cerling, 1991).

It was shown by Dörr and Münnich (1980) that soil-CO₂ becomes enriched in the heavy isotope of carbon due to diffusion compared to its precursor i.e. plant-CO₂. The exact value of this enrichment depends on the CO₂ concentration in the soil, sampling depth and other parameters. However, for mature soils of Lameta and for depths greater than 25 cm, a value of 4.4‰ for enrichment can be assumed (cf. Cerling, 1991). Carbonates formed from this enriched soil-CO₂ are further enriched by 9.8‰ , by equilibrium isotopic fractionation at 25°C as pointed out before. Therefore the δ -value of the Lameta associated plant-CO₂ can be derived from the δ -value of the pedogenic carbonates (Table 1).

Estimated $\delta^{13}\text{C}$ values of plant-CO₂ for the Lameta vegetation (Table 1) fall in the range of C₃ type plants, but have a higher average value of -23.4‰ compared to the expected average of -26‰ . This difference can be due to:

- (1) Species of C₃ plants involved; for example, the C₃ plants of modern desert ecosystems are often several per mil enriched in $\delta^{13}\text{C}$ (Ehleringer, 1989).
- (2) Presence of C₄ and CAM type biomasses intermixed with the C₃ type.
- (3) Contribution from atmospheric CO₂.

While little or no knowledge is available regarding the ancient C₃ species, it is generally believed that the plants utilizing C₄ or CAM photosynthetic pathways did not evolve until Miocene (Cerling, 1991; Quade et al., 1989; Mack et al., 1991). Moreover, total biomass of CAM plants is usually insignificant in most ecosystems except in some of the deserts. Therefore, the CO₂ in the Lameta soil was probably derived from only two sources: the C₃ plants and the atmosphere. Using Fig. 3 of Cerling (1984) one can estimate a contribution of

about 15% by the atmospheric CO₂ to explain the observed enrichment in the Lameta samples relative to the expected average $\delta^{13}\text{C}$ value.

3.8. Atmospheric CO₂ content in Late Cretaceous

In view of the sizable contribution of atmospheric CO₂ in soil CO₂ even at depths exceeding 25 cm, one can estimate the the partial pressures (PCO₂) of the atmospheric CO₂ under certain assumptions following the procedure outlined by Cerling (1991). It was indicated earlier that the Lameta soils were developed in hot and semiarid climate with seasonal rainfall and considerable amount of vegetation was supported by these soils. The PCO₂ of soil CO₂ and the atmospheric CO₂ usually have a difference of about 3000 ppmV or less in desert soils. Considering the semi-arid climatic setup during the Lameta time this difference is expected to lie between 3000 and 5000 ppmV. Taking these values as limits and the average $\delta^{13}\text{C}$ value of -9.1‰ for the Lameta carbonates fig. 7 of Cerling (1991) can be used to derive a range of 800–1200 ppmV for the PCO₂ of the Lameta atmosphere. The ≈ 3 –4 times higher partial pressure of CO₂ in the Late Cretaceous Lameta atmosphere compared to the present-day value corroborates well with Berner's (1991) estimates of atmospheric PCO₂ at the end of the Cretaceous.

This estimate is unquestionably preliminary and rests on many assumptions. Nevertheless it fits in nicely with the other two estimates given in Cerling (1991) i.e. 2500 ppmV for the Lower Cretaceous and less than 600 ppmV for Eocene. Taken together, these results show a monotonic decline in the PCO₂ levels from the beginning of the Cretaceous till recent time, i.e. from a value of 2500 to 300 ppmV. However, more work is required before the potential of pedogenic carbonate in deriving the palaeo-PCO₂ level is firmly established.

4. Conclusions

In central India, a sequence of calcareous sediments of Upper Cretaceous age, known as Lameta Formation, is exposed beneath the Tertiary Deccan

Traps. Extensive soils and associated pedogenic carbonates formed on these sediments in alteration with fluvial depositional cycles. The pedogenic carbonates from these Cretaceous soils were analysed for oxygen and carbon isotopic composition to infer the palaeometeorological palaeovegetational regime in Central part of the Indian Continent. The oxygen isotope composition of these carbonates ranges from -6.7 to -8.9‰ (excluding two outliers). Assuming the fractionation model of earlier workers and a formation temperature of 25°C in soil, these data can be used to derive isotopic composition of the meteoric water in Cretaceous Central India. The average $\delta^{18}\text{O}$ of this meteoric water is estimated to be -8‰ (w.r.t. SMOW) which is considerably lighter compared to the composition of modern precipitation in Central India i.e. about -3‰ .

The lighter isotopic composition of the meteoric water signifies the difference in the nature of the meteorological system operating at that time, owing to a different palaeogeographical position of a probably bigger Indian landmass. The low value of $\delta^{18}\text{O}$ can best be explained by a combination of effects arising from highly seasonal (monsoon-like) and slightly more intense rain fall regime in a rain shadow zone and a more pronounced "continental effect" due to a bigger size of the Indian continent.

The carbon isotopic composition of the Lameta carbonates range from -7.1 to -10.7 with an average of -9.1‰ suggesting a series of soils dominated by C_3 type of vegetation. The estimated average composition of the vegetation (-23.4‰) is enriched by about 3‰ compared to the modern day C_3 vegetation. This is probably due to an admixture of atmospheric CO_2 ($\delta^{13}\text{C} = -6.5\text{‰}$) contributing about 15% of the total CO_2 in the soil. This contribution of atmospheric CO_2 allows one to estimate the partial pressure of CO_2 in the Late Cretaceous atmosphere using the model of Cerling (1991) under certain assumptions. The palaeo- PCO_2 level at that time is estimated to be around 800–1200 ppmV. If verified by future studies this will indicate that the PCO_2 decreases monotonically from 2500 ppmV in the Early Cretaceous to 300 ppmV in the Holocene.

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