CHAPTER-4

PALAEOVEGETATIONAL RECONSTRUCTION BASED ON EARLY DIAGENETIC CARBONATE CEMENT OF SANDSTONE NODULES

4.1 Introduction

It is now well established that a remarkable transition in vegetation took place in the Indian subcontinent during late Miocene. Based on carbon isotope ratio of soil carbonates from palaeosol beds of Siwalik sections in Pakistan and Nepal Quade et al (1989, 1995) showed that around 7 Ma ago there was a sudden invasion of C_4 plants. Subsequent analysis showed that the timing of transition from pure C_3 to mixed C_3-C_4 era was different in different Siwalik sections. For example, in the Pakistan Siwalik, expansion of C_4 plants started rapidly at around 7.7 Ma (Quade et al., 1989) whereas in the Surai Khola section of Nepal Siwalik it was 0.7 Myr later (Quade et al., 1995). Our study from the Kangra valley, India, showed absence of C_4 plants before 6 Ma (Sanyal et al., 2004a).

As mentioned before, the presence of extensive Siwalik exposures in many parts of present-day India provides an opportunity for further studies on this topic. However, scarcity of soil carbonate nodules in Indian Siwalik sections prevents accurate reconstruction of the timing and nature of C_3 to C_4 transition in these sections. In this context, it is worthwhile to explore if the carbon isotope ratio of early diagenetic carbonate cement in sandstone nodules can be used to reconstruct a picture of palaeovegetation. Since the cement is primarily derived from dissolved carbonate in shallow ground water, which is in isotopic equilibrium with local plant-derived CO_2. Signature of vegetation change can have some reflection in $\delta^{13}C$ of the cement. However, a precondition for signal preservation in cement is negligible post depositional changes (Quade and Roe, 1999).

Here we present an investigation carried out in two Siwalik sections: Mohand Rao of Dehra Dun sub-basin (DSB) in Uttaranchal and Haripur Khol of Subathu sub-basin (SSB) in Himachal Pradesh (Fig.2.1). In the Mohand Rao section, early diagenetic sandstone nodules are continuously present between 9 to 5 Ma whereas only a few nodule bearing soil horizons are seen. In the Haripur Khol section (age 6 to 1 Ma) both soil carbonate nodules as well as early diagenetic sandstone nodules are present throughout the section thus providing an opportunity for intercomparison and validation of cement data. In this chapter early diagenetic carbonate cement of sandstone nodules has been referred to as "DCCN", soil carbonate nodules as "SCN" and carbonate cement of sandstones as "CCS" for simplicity.

4.2 Evidence for early diagenetic character of the cement

Quade and Roe (1999) were the first to use carbon isotope ratio of DCCN from Siwalik sections of Pakistan to reconstruct palaeovegetation. The early diagenetic sandstones occur in the field as densely cemented nodules that stand out in relief in outcrops upon weathering. For the present study, rounded nodules (Fig.4.1) and ellipsoidal nodules with long axis parallel to bedding planes (Fig.4.2) were chosen. In this type of nodules, calcite cement constitutes 35-60 % of matter by volume, which is consistent with the porosity of slightly compacted or uncompacted sands (Fig.4.3) (Quade and Roe; 1999).

The carbon and oxygen isotope ratios at various points in the section of a nodule were determined to check isotopic homogeneity (Fig.4.4). Carbon isotope values at different points vary from –0.5 to –1.1 ‰ with an average of –0.8±0.2‰ and the corresponding oxygen isotope ratio varies from –11.6 to –11.9 ‰ with an average of –11.8± 0.1‰ (n=14). The dispersion in $\delta^{13}C$ and $\delta^{18}O$ values is quite small. This shows that the nodules are isotopically un-zoned and do not contain significant amount of later generation cements which may complicate the issue by having different and possibly variable composition.

4.3 Mudstone facies with concretions in Mohand Rao Section

As mentioned in section 2.4b, abundance of mudstone facies is low in Mohand Rao section. The mudstone occurs as discontinuous lenticular body within the multistoried sandstone beds (between 350 and 1400 m). In the lower and upper part, these beds are 0.5 to 8 m thick and gray (rarely brown) in color. Green mottling is common in the mudstone and palaeosols. Mudstone shows evidence of biological activities and comprises vertical, unlined burrows (skolithos) and surface traces (sinusitis). Pedogenic concretions are common locally and mudstones show immature soil profile (Kumar, 2004)

4.4 Results

Isotopic analysis of DCCN from Mohand Rao section shows that at around 9 Ma DCCN $\delta^{13}C$ is about –10.5 ‰ and then progressively becomes enriched with time. At around 7.5 Ma, the $\delta^{13}C$ is –3.2 ‰. From 7.5 to 6 Ma the $\delta^{13}C$ is almost constant at about zero per mil. In Haripur Khol section (6 to 1 Ma), $\delta^{13}C$ of DCCN varies from –3.5 ‰ to 0.4 ‰ (Fig.4.5a, Table 4.1).

The corresponding $\delta^{18}O$ value of DCCN in Mohand Rao section varies from –8.9‰ to –13.6 ‰ and in Haripur Khol section from –9.9 ‰ to –13.6 ‰ (Fig.4.5b, Table 4.1).

Table 4.1 *Carbon and oxygen isotope ratio of DCCN from Mohand Rao and Haripur Khol sections. Values are relative to VPDB in ‰.*

DCCN from Mohand Rao Section				**DCCN form Haripur Khol section**			
Sample No	Age (Ma)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Sample No	Age (Ma)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
MD-1s-N	9.0	–10.5	–10.8	HP-12S	5.4	–2.0	–9.9
MD-3S-N	8.9	–6.1	–12.1	HP-A24S	4.7	–2.8	–12.4
MD-4S-N	8.7	–6.6	–11.7	HP-23S	3.9	–0.9	–13.6
MD-5S-N	8.6	–8.4	–13.6	HP-32S	3.6	–3.5	–11.7
MD-7S-N	8.2	–6.0	–8.9	HP-33S	3.3	0.4	–12.3
MD-8S-N	8.0	–4.0	–12.0	HP-38S	3.2	–0.2	–12.5
MD-10S-N	7.5	–3.2	–11.2	HP-39S	3.0	–0.7	–12.7
MD-19S-N	6.5	–0.3	–12.6	HP-40S	2.8	–3.2	–12.6
MD-20S-N	6.5	–0.7	–11.2	HP-41S	2.8	–0.4	–12.4
MD-21S-N	6.4	–0.3	–10.5	HP-50S	2.6	–2.3	–11.8
MD-22S-N	6.3	–0.2	–12.1	HP-51S	2.6	–0.6	–11.4
MD-24S-N	6.0	–2.0	–12.1	HP-53S	2.5	–0.4	–10.7
				HP-58S	2.4	–2.8	–10.7

Table 4.2 *$\delta^{13}C$ and $\delta^{18}O$ of SCN and $\delta^{13}C$ of organic matter associated with SCN from Mohand Rao. Values are relative to VPD in ‰.*

Sample No	Age (Ma)	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C_{Org.}$	Sample No	Age (Ma)	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C_{Org.}$
MD-1C	9.0	–10.8	–8.8	–24.4	MD-2(C)	5.4	–4.3	–8.9	
MD-2C	8.5	–9.2	–7.4	–24.5	MD-4(C)	5.3	–1.6	–7.1	–19.0
MD-2C1	8.5	–9.5	–9.6	–24.4	MD-5(C)	5.3	–2.7	–7.8	–22.6
MD-7C(N)	8.2	–7.8	–9.0	–25.2	MD-6(C)	5.3	–3.3	–8.5	–24.3
					MD-7(C)	4.8	0.1	–6.8	–17.4

Mohand Rao section and Haripur Khol section are about 100 km apart and both the places are located in a monsoon sensitive region. As the geographical configuration of India has not changed much from the Siwalik time, the isotopic data from Mohand Rao and Haripur Khol sections can be combined to make two composite plots representing regional time variation of carbon and oxygen isotope ratios of DCCN (Fig.4.5) respectively. In such composite plot carbon isotope ratio shows enrichment starting from 9 Ma and reaches its maximum value at around 7.0 Ma. Subsequently, till about 1.8 Ma the $\delta^{13}C$ is reasonably constant with some scatter in data (within ± 1‰) (Fig.4.5a). The $\delta^{18}O$ of sandstone nodules in composite plot does not show any systematic variation with time (Fig.4.5b).

The $\delta^{13}C$ of the SCN (n=9) in Mohand Rao section ranges from –10.8 ‰ to –7.8 ‰ between the time period 9 to 8 Ma and from 5.4 to 4.8 Ma, the $\delta^{13}C$ ranges from –4.3 to 0.1‰ (Fig.4.6a, Table 4.2) and the $\delta^{13}C$ of associated organic mater ranges from –25.2 to –24.4 ‰ and –17.4 ‰ to –22.6 ‰ respectively (Fig.4.6c, Table 4.2). The $\delta^{18}O$ value of SCN in the time range 9 to 8 Ma varies from –9.6 ‰ to –7.4 ‰ and in between 5.4 to 4.8 Ma the value varies from –8.9 ‰ to –6.8 ‰ (Fig.4.6b, Table 4.2).

4.5 Discussion

4.5.1 Carbon isotope ratio of soil carbonate and early diagenetic carbonate cement of sandstone

In section 3.3.1 it was argued that carbon isotope ratio of soil carbonate could be used to reconstruct vegetation scenario as the soil carbonate forms in isotopic equilibrium with soil CO_2, which, in turn, represents local vegetation. Carbon isotope ratio in shallow ground water just below the soil zone is also in or near isotopic equilibrium with plant-derived CO_2 as demonstrated by ^{14}C and stable isotope studies (Pearson and Hanshaw, 1970; Fritz et al., 1978; Bath et al., 1979; Deak, 1979; Andrews et al., 1984; Wassennar et al., 1992; Leaney and Herczeg, 1995; Clark et al., 1997). Ground water calcite cement should also form in equilibrium with this reservoir, as long as it forms shortly after burial without any interaction with carbon sources other than plant-CO_2. Hence, carbon isotope ratio of early diagenetic carbonate cement could also be used to reconstruct the type of vegetation (Quade and Roe, 1999).

Fig. 4.1 a) *Occurrence of rounded nodules in sandstone bed* b) *Close view of the same Rounded sand nodule.*

Fig.4.2 *Ellipsoidal sandstone nodules with long axis parallel to bedding.*

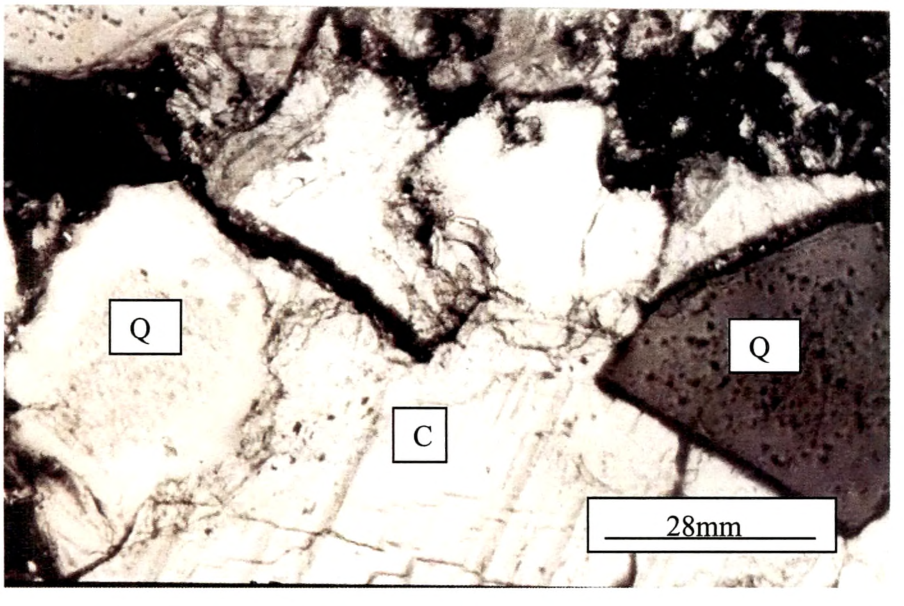

Fig.4.3 *Thin section shows two quartz grains separated by calcite cement indicating that cementation of sediments occurred before significant burial. The calcite cement constitutes 35-60 % of the nodule which is consistent with the porosity of slightly compacted or uncompacted sand (Q= Quartz; C= carbonate cement) (Quade and Roe, 1999).*

The carbon isotope ratio of DCCN from Mohand Rao section indicates that around 9 Ma the vegetation was exclusively of C_3 type and subsequently it shows the appearance of C_4 plants. Gradually, the C_4 plants started dominating the ecosystem and reached its acme at around 7.0 Ma and continued to dominate the vegetation in a mixed C_3-C_4 environment. The carbon isotope ratio of SCN from the same section also shows the presence of C_3 type of plants between 9-8 Ma (except one sample possibly indicating isolated appearance of C_4 plants, Fig.4.6a). Around 5 Ma, the vegetation was characterized by both C_3 and C_4 types of plants with the dominance of C_4 type of plants in the ecosystem.

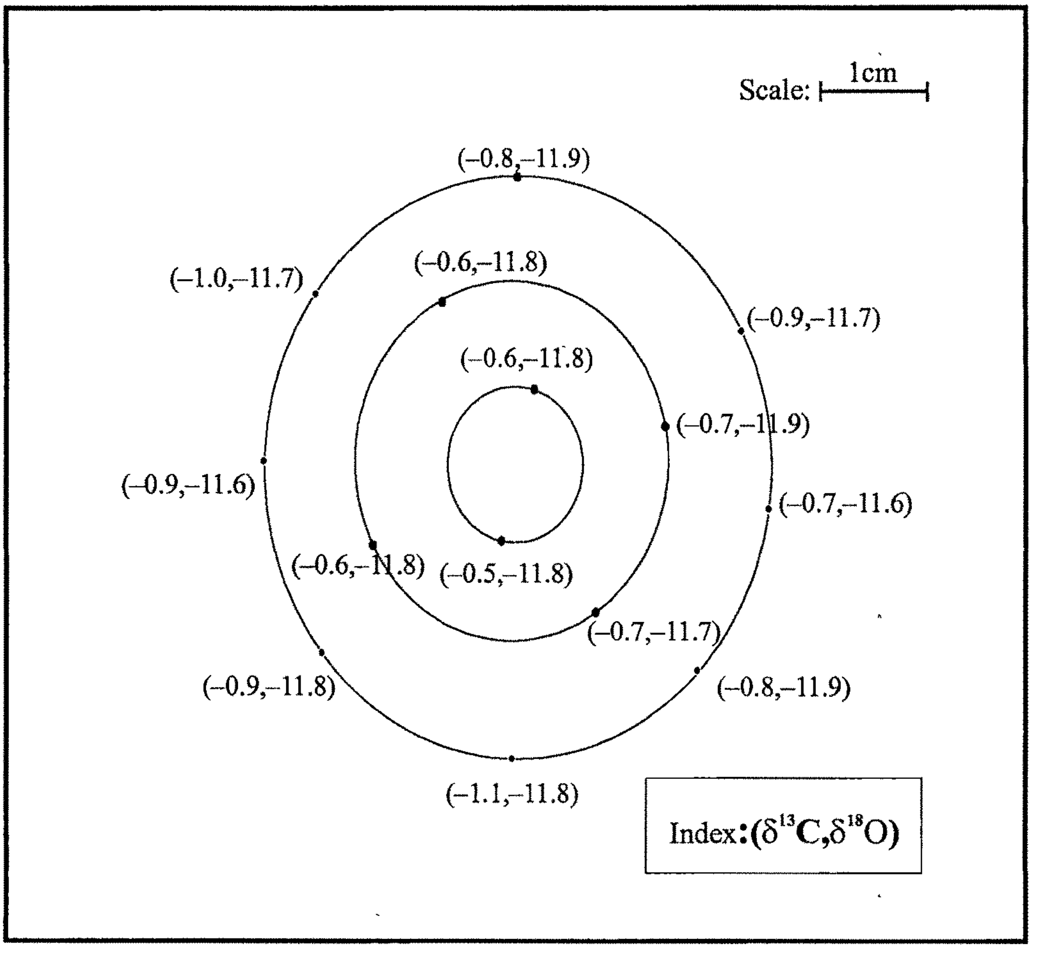

Fig.4.4 *Carbon and oxygen isotope ratio of carbonate cement in a DCCN. The uniformity in carbon (−0.8±0.2) and oxygen isotope ratios (−11.8±0.1) throughout the nodule section indicates that the nodule is isotopically un-zoned and does not contain significant amount of later generation cements.*

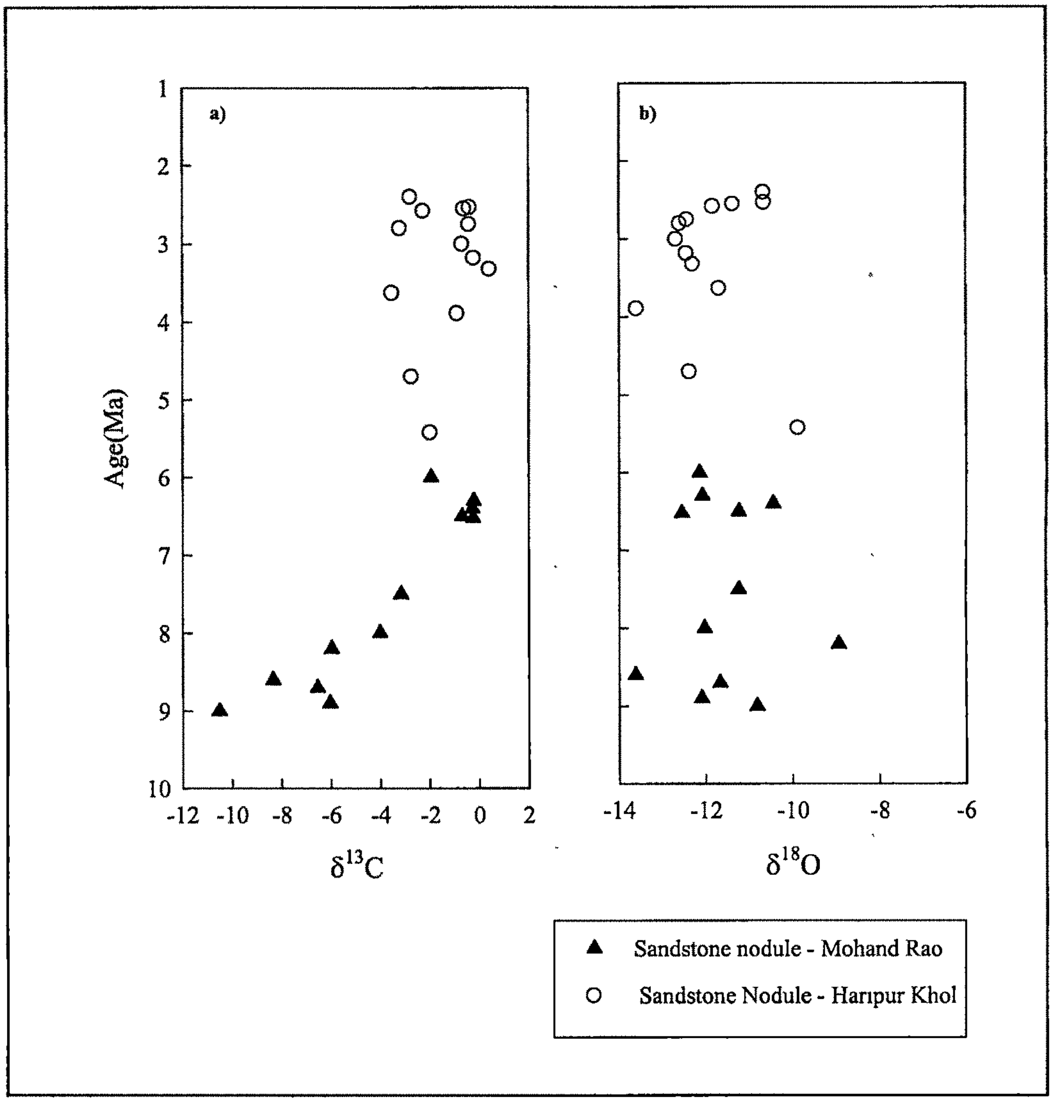

Fig.4.5 *Composite plot of isotope ratios against age for sandstone nodules from Mohand Rao and Haripur Khol sections. a) Carbon isotope ratios of DCCN show that at around 9 Ma the vegetation was mainly C_3 type and subsequently C_4 plants started appearing. By 6 Ma abundance of C_4 plants reaches a high value and remains so thereafter. b) Oxygen isotope ratios of DCCN do not show any systematic variation. The dispersion in $\delta^{18}O$ may be due to variable contribution of river water into shallow groundwater.*

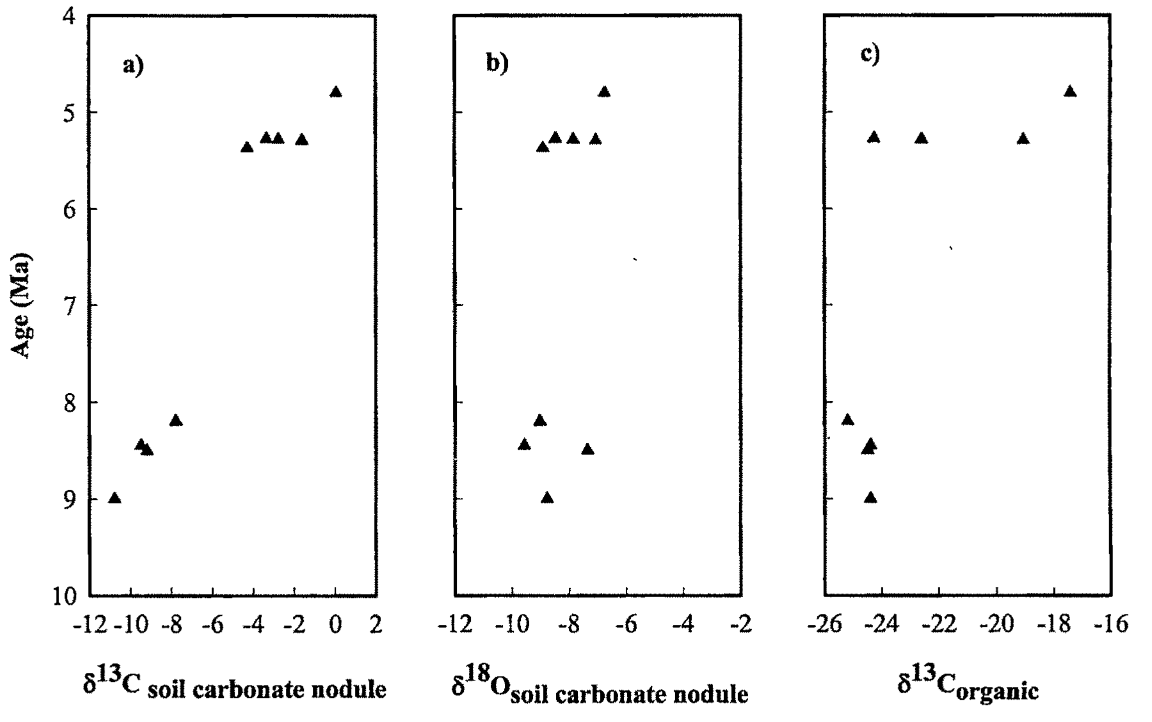

Fig.4.6 *Time variation of carbon isotope ratio of soil carbonate nodules (a) and associated organic matter (c) from Mohand Rao section indicates that around 9 Ma the vegetation was purely C_3 type, whereas a mixed C_3-C_4 environment existed around 5 Ma. b) Oxygen isotope ratio of soil carbonate from Mohand Rao section at about 9 Ma and 5 Ma are almost similar and comparable to the oxygen isotope ratio of soil carbonate from Kangra valley and Haripur Khol section for the same time period. These oxygen isotope values are depleted compared to the values obtained in other section for different time periods (Chapter3). The depletion has been attributed to an intensification of the monsoon.*

Studies based on carbon isotope ratio of SCN from Siwalik showed that the transition from C_3 to mixed C_3-C_4 type was abrupt with distinct difference in time of appearance of C_4 plants in different sections (Quade et al., 1989; 1995; Quade and Cerling, 1995; Sanyal et al., 2004a). The carbon isotope ratio variation of DCCN from Mohand Rao section offers a relatively continuous picture and indicates that the appearance of C_4 plants was earlier compared to other sections and the transition from C_3 to mixed C_3-C_4 plant regime was gradual in this area. C_4 plants appeared just after 9 Ma and took around 2 Myr to reach its maximum abundance.

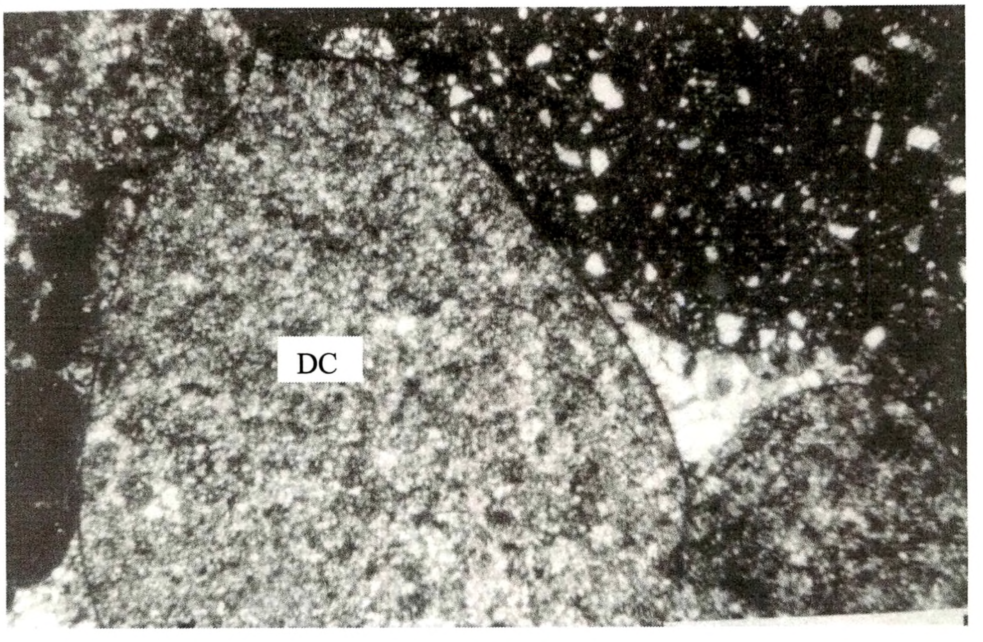

Fig.4.7a *Detrital carbonate (DC) in sandstone. The abundance of the detrital carbonate varies from 5-20%.*

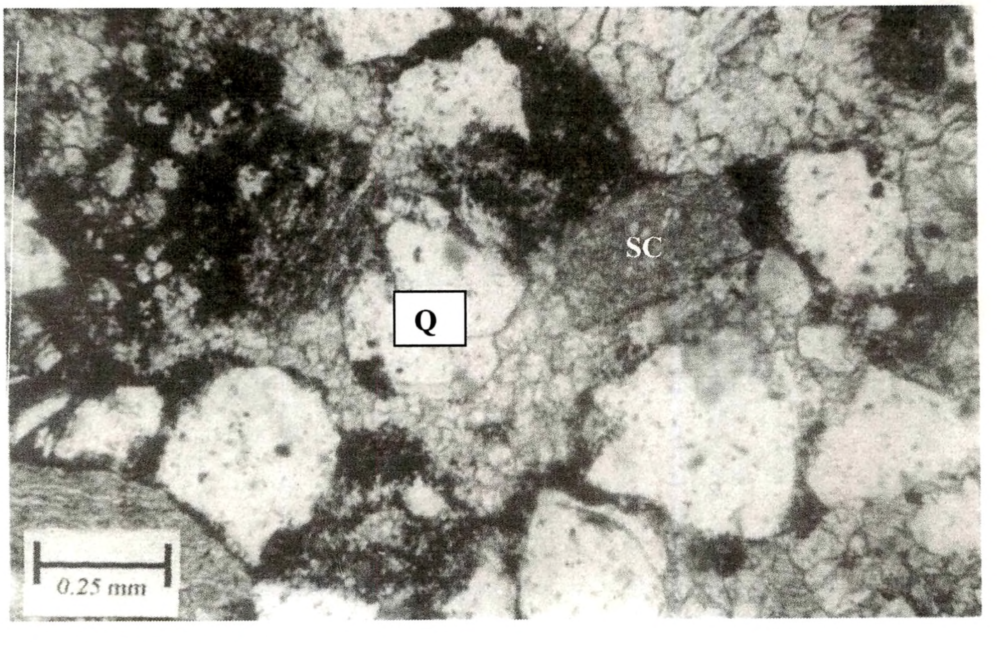

Fig.4.7b *Thin section showing blocky micritic grains (SC) possibly representing intrabasinal soil carbonate. Q= Quartz.*

4.5.2 Comparison between $\delta^{13}C$ of early diagenetic carbonate and soil carbonate

The main source of carbon in SCN and DCCN is plant-derived CO_2. In addition, minor (5-20 %) amount of detrital carbonate is also present as seen from thin section analysis of sandstone nodules. Our observation of low detrital amount is consistent with the earlier published data (Quade and Roe, 1999). The detrital carbonate in the sandstone is probably marine carbonate, derived from Himalayan sediments (Fig.4.7a). In some cases, fragments of soil carbonate are also seen (Fig.4.7b). Since the Himalayan carbonates have $\delta^{13}C$ close to zero which is quite different from SCN values ranging from −10 to +2‰ (depending on vegetation cover on soil) contribution of detrital carbonate may change the original $\delta^{13}C$ signature of groundwater cement. Fig.4.8 shows the correlation between $\delta^{13}C$ values of SCN and DCCN where samples of DCCN and SCN represent adjacent beds. The scatter of the points and deviation from 1:1 line probably points towards variable but minor contribution of detrital carbonates in sandstone nodules. It is also possible is that $\delta^{13}C$ values of DCCN reflect vegetation over a broader area than one represented by average SCN (Quade and Roe, 1999). In the Himalayan foothills, the active floodplain is dominated by C_4 plants in post- 6 Ma period (Quade et al., 1995; Sanyal et al., 2004a) whereas C_3 forest covers higher abandoned terraces and adjacent frontal Himalayan foothills. Therefore, the $\delta^{13}C$ of SCN and DCCN from adjacent beds may differ due to variable contribution from water draining C_3 sources and influencing DCCN.

4.5.3 Oxygen isotope ratio of soil carbonate and early diagenetic carbonate cement of sandstone

The oxygen isotope ratio of SCN and DCCN depends on several factors such as oxygen isotope ratio of ambient water, the temperature at which the carbonate precipitates, post depositional (late) diagenetic changes etc. If diagenetic effect is not significant it is possible to derive information about rainfall variation in the past from $\delta^{18}O$ data. It was discussed in section 3.4 that oxygen isotope ratio variation in SCN from the Kangra Valley and Haripur Khol section of Indian Siwalik reflects a change in amount of rainfall in the past (Sanyal et al., 2004a). It is seen that the oxygen isotope ratio variation from the above sections is characterized by two phases of depletion, which occurred around 10.5 Ma and 5.5 Ma reflecting increase in the intensity of summer monsoon rainfall (Sanyal et al., 2004a). In contrast, the oxygen isotope ratio of DCCN does not show any systematic variation with time (Fig.4.5b). It is noted that, at a given stratigraphic level, the average $\delta^{18}O$ value of DCCN is depleted (maximum depletion being about 4‰) compared to the average $\delta^{18}O$ of SCN from the same level (Fig.4.5b). The cause of this depletion may be related to the difference in the source of water. In case of SCN the source of water is local rainfall whereas, shallow ground water

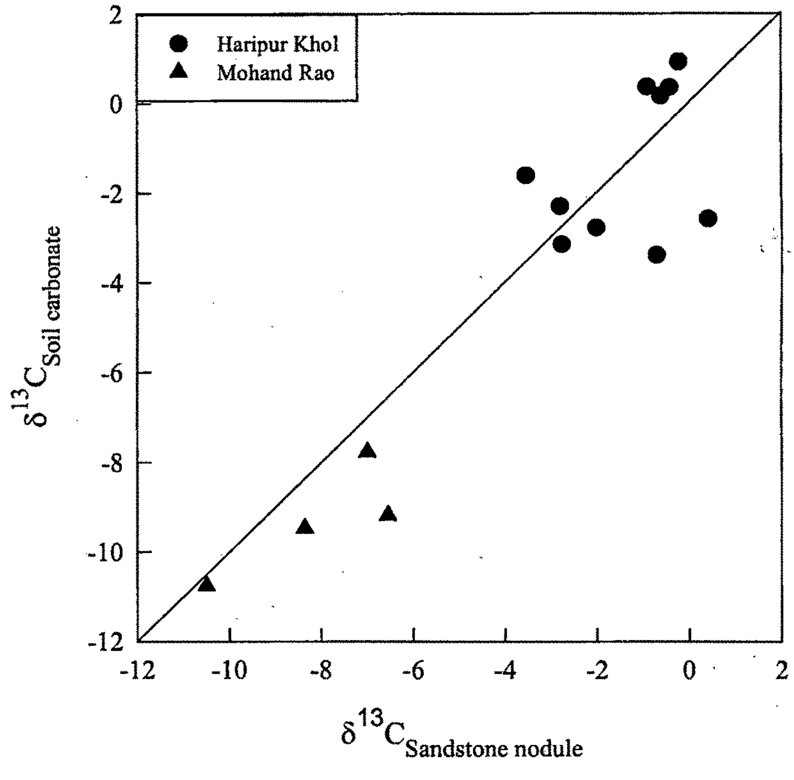

Fig.4.8 *Correlation between the carbon isotope ratios of soil carbonates and early diagenetic carbonate cements of sandstones. The plot represents samples taken from adjacent beds. The scatter of the points and deviation from 1:1 line points towards variable but minor contribution of detrital carbonates in sandstone nodules.*

from which carbonate cement in sandstones precipitates could have contribution from other sources. In the Indo-Gangetic plain, during the post monsoon period the river water feeds the groundwater. The average $\delta^{18}O$ of water from tributaries of Yamuna river (which is close to the sampling sections) for the period just after monsoon is –9.7‰ (SMOW) (Dalai et al., 2002). If we take this as representative value of Dehra Dun sub-basin and Subathu sub-basin groundwater, the $\delta^{18}O$ of the corresponding carbonate would be around –11.6 ‰ [considering the annual average temperature of the area ~25°C and using the fractionation factor between calcium carbonate and water: $1000\ln\alpha^{carbonate}_{water} = 2.78 \times 10^6 / T^2 - 2.89$ (Friedman and O'Neil, 1977) where $\alpha^{carbonate}_{water} = (1000 + \delta^{18}O_{carbonate})/(1000 + \delta^{18}O_{water})$] which is close to the observed average $\delta^{18}O$ (–11.7‰) value of DCCN. The close agreement supports our suggestion regarding depleted ^{18}O values of the cement. It is also of interest to know the $\delta^{18}O$ of carbonate cements from sand bodies (CCS) other than DCCN. The $\delta^{18}O$ value of CCS sheets ranges from –10.3 ‰ to –15.3 ‰ with an average of –13.6±2 ‰ (n=21), which is depleted compared to the average $\delta^{18}O$ value of DCCN (–11.7±1.1‰). This can be explained by precipitation/re-equilibration of cement in sandstone sheets at higher burial temperature since an increase in temperature causes depletion in the $\delta^{18}O$ of carbonate. In addition, water-rock ratio (W/R) also affects the final $\delta^{18}O$ of carbonate during precipitation/re-equilibration. The W/R ratio can be expressed as: $W/R = (\delta^{18}O^{final}_{carbonate} - \delta^{18}O^{intiall}_{carbonate})/(\delta^{18}O^{initial}_{water} - \delta^{18}O^{finall}_{water})$ (Quade et al.,1995) where superscript 'initial' and 'final' refer to the $\delta^{18}O$ values of carbonate and water before and after equilibrium isotopic exchange. Using above equations it can be shown that at infinite water-rock ratio the observed depletion in the carbonate cement of sandstone sheet (~2‰) would require a temperature of about 33 °C which could be reached within 400 m of burial assuming geothermal gradient to be 20°C/km.

Oxygen isotope ratio of DCCN from Pakistan Siwalik ranges from –11.6 to –6.6 ‰ (Quade and Roe, 1999). Overall, the $\delta^{18}O$ increases upsection but it has an excursion toward lower values at around 7 Ma. However, the composite section, which has been made from Mohand Rao and Haripur Khol section (Fig.4.5b) does not show any such excursion around 7 Ma. There is a clear swing toward enriched values at ~3 Ma in both the Indian and Pakistan sections. In Pakistan section the $\delta^{18}O$ at around 3 Ma is –10‰ and subsequently it increases to –7‰. In the Indian section, the $\delta^{18}O$ of sandstone nodule around 3 Ma is –12.7‰ and subsequently it reaches the value ~ –10.7 ‰ (Fig. 4.9).

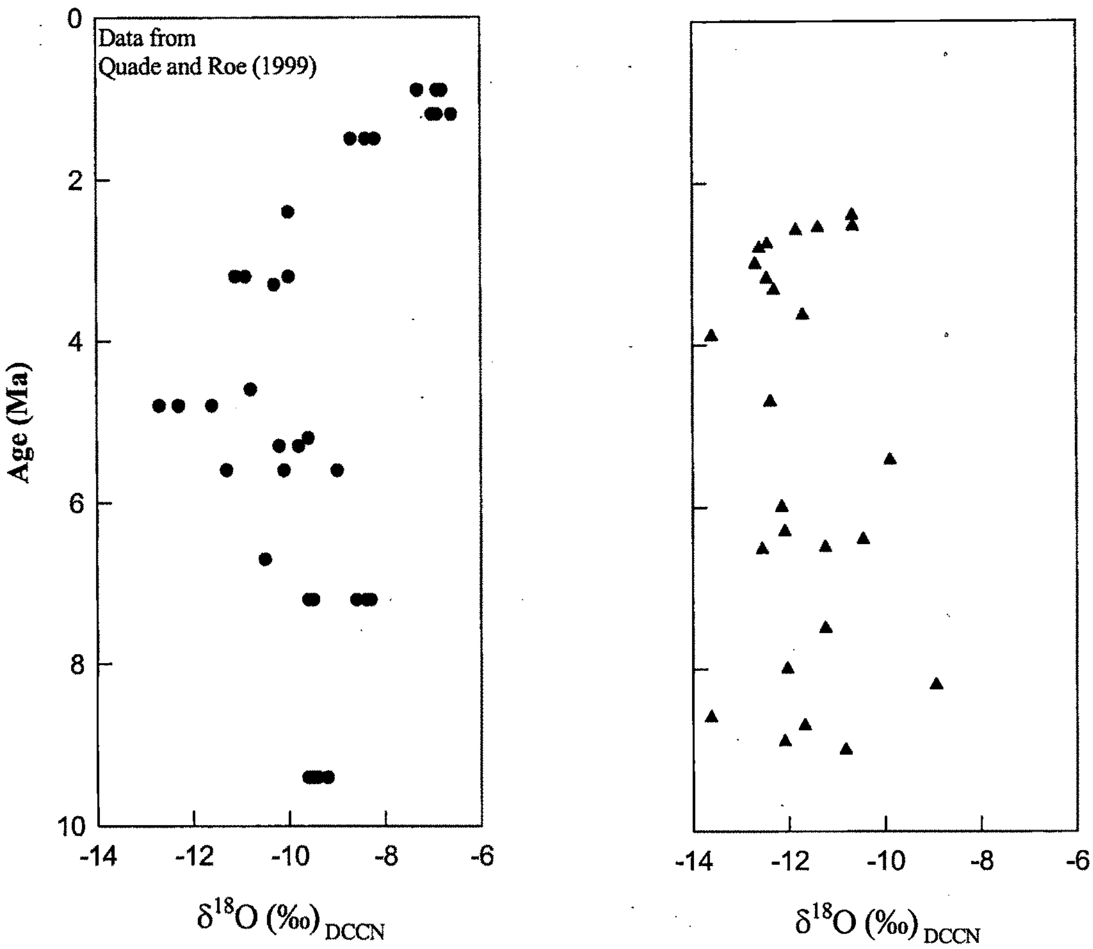

Fig.4.9 *Comparison between oxygen isotope ratio of DCCN from Pakistan and Indian sections. In Pakistan section overall $\delta^{18}O$ increases up-section with an excursion toward lower values at around 7 Ma. This excursion is missing in Indian sections. There is a clear swing toward enriched values at ~3 Ma in both the Indian and Pakistan sections.*

The $\delta^{18}O$ of DCCN in Pakistan section seems to be enriched compared to the $\delta^{18}O$ of Mohand Rao and Haripur Khol section if we compare samples in the same age bracket. This difference in $\delta^{18}O$ ranges up to about 3.5‰. One probable cause for the depleted $\delta^{18}O$ in Indian section is depleted value of local rainwater. Mohand Rao and Haripur Khol sections are located in a region, which receives very high rainfall (550 mm during SW monsoon, JJAS; Indian Meteorological Department, 1970). On the other hand, the Pakistan Siwalik is located at the farthest end of the Indian monsoon system and receives only 170 mm (average of SW monsoon, Rao, 1981) rain. At low latitudes, the average monthly rainfall and the mean monthly $\delta^{18}O$ are usually negatively correlated; an increase of 100 mm of precipitation is associated with a decrease in $\delta^{18}O$ by 1.5 ‰ (Yurtsever and Gat, 1981). Hence, the $\delta^{18}O$ of rainwater in Mohand Rao and Haripur Khol area could be depleted by ~4 ‰ compared to the $\delta^{18}O$ of rainwater in Potwar plateau in Pakistan. This is close to the observed $\delta^{18}O$ difference between the two carbonates.

It is also noted that the trend of oxygen isotope ratio of SCN from Kangra valley and Haripur Khol section differ from the oxygen isotope ratio trend in Pakistan (Quade et al., 1989; Sanyal et al., 2004a). As mentioned earlier, the oxygen isotope ratio of SCN from Kangra valley and Haripur Khol section is characterized by two phases of depletion at around 10.5 Ma and 5.5 Ma. The oxygen isotope ratio of SCN from Potwar Plateau is characterized by enrichment starting from 8 Ma and reaching a maximum at around 5 Ma (Quade et al., 1989).

Though based on limited samples (n=9), the oxygen isotope ratio of SCN of Mohand Rao section is consistent with the results of Kangra valley and Haripur Khol section. The average oxygen isotope ratio at about 9 Ma and 5 Ma is around –9‰ and –8‰ (Fig.4.6b). Previous study from the Kangra and Haripur Khol section showed similar oxygen isotope ratios for these two time periods. These values are depleted compared to other time periods of the section (Sanyal et al., 2004a) and have been attributed to an intensification of monsoon. The present data lends support to the same conclusion.

4.6 Timing and nature of change in vegetation in various Siwalik sections of Pakistan and India

Carbon isotope ratio of SCN from Potwar Plateau of Pakistan Siwalik showed appearance of C_4 plants at around 7.7 Ma; the abundance of C_4 plants reached a maximum by 6.5 Ma. The appearance of C_4 plants was preceded by a change in rainfall pattern (Table 4.3). In Nepal Siwalik, the appearance of C_4 plants was about 0.7 Myr later compared to Pakistan Siwalik while change in rainfall pattern was observed at around 6 Ma. In Kangra Valley-Haripur Khol section of Indian Siwalik, C3 plants dominated vegetation up to 6 Ma. Abrupt change in vegetation from pure C_3 to mixed C_3-C_4 occurred after 6 Ma. In Kangra Valley-Haripur Khol section intensification of rainfall (monsoon) was observed at around 10.5 Ma and 6 Ma. Appearance and expansion of C_4 plants coincided with the second phase of monsoon intensification. In Mohand Rao section, appearance of C_4 plant was observed at around 9 Ma and it took nearly 2 Myr to reach maximum abundance of C_4 plants.

Present day rainfall data in these sections (where available) show variation in rainfall amount during southwest monsoon. The mean rainfall during southwest monsoon in Potwar Plateau is 170 mm (average of SW monsoon, Rao, 1981), in Kangra valley 550 mm and in Mohand Rao section 440 mm (taken from Dehra Dun rainfall

Table 4.3 *Timing and nature of change in vegetation and timing of rainfall pattern change in different Siwalik sections.*

Section	Timing of appearance of C_4 plants	Nature of change in pure C_3 to mix C_4-C_3 vegetation	Timing of rainfall change
Potwar Plateau, Pakistan	7.5 Ma	Rapid, took 1.5 Myr to reach maximum abundance of C_4	8 Ma
Surai Khola, Nepal	6.8 Ma	Rapid, took 1.5 Myr to reach maximum abundance of C_4	6 Ma
Kangra Valley - Haripur Khol, India	6 Ma	Abrupt	10.5 Ma and 6 Ma
Mohand Rao, India	9 Ma	Gradual, took 2 Myr to reach maximum abundance of C_4	Data scanty, but comparable with Kangra Valley-Haripur Khol data

data). The difference in the amount of rainfall in these areas suggests that climatic conditions were probably different in them. This might have played an important role in controlling the timing and nature of change in vegetation. However, direct correlation between rainfall amount and vegetation cannot be clearly established.

4.7 Conclusions

Carbon isotope ratio of early diagenetic carbonate from sandstone nodules shows that C_4 plants started to appear in Mohand Rao section at around 9 Ma, which is somewhat earlier compared to the other Indian sections. Also, the transition from pure C_3 type of plants to mixed C_3-C_4 plant regime was gradual. The carbon isotope ratio of sandstone nodules from Haripur Khol section showed presence of mixed C_3-C_4 vegetation with C_4 dominating the ecosystem for the time period 6 to 1 Ma. The vegetational transition is, therefore, now established from four Indian sections albeit with temporal difference in their onset. Oxygen isotope ratio of early diagenetic carbonate cement shows variable contribution of river water into shallow groundwater. The oxygen isotope ratio of soil carbonate indicates intensified monsoon at around 9 Ma and 5 Ma.