CHAPTER-8

CONCLUSIONS AND FUTURE STUDIES

8.1 Conclusions

A major climatic change occurred in the Indian subcontinent during Miocene time as a consequence of uplift of Himalaya and Tibetan plateau resulting in alteration of air circulation (Ruddiman and Kutzbach, 1989). It is believed that this change in circulation of air established the monsoon system in Asia. However, the monsoon intensified only after Himalaya attained a critical height. There was another important consequence. Uplift of Himalaya caused increase in chemical weathering, which, in turn, reduced CO_2 concentration in the atmosphere since weathering takes place through CO_2 consumption. Change in climate along with CO_2 concentration in atmosphere also resulted in vegetational change in the Himalayan foothills.

In the present study, we attempted to understand the details of monsoonal rainfall variation, contemporary CO_2 concentration in the atmosphere and associated vegetational change based on analysis of sediments from Himalayan foothills, which are collectively known as Siwalik Group. Siwalik sedimentary sequence comprises of weathered materials from Himalayan rocks carried by various rivers and deposited in foreland basins more or less continuously for the last 20 Myr. In India, the Siwalik sediments are exposed in a WNW and ESE direction, which is almost parallel to the summer monsoonal track. The effect of rainfall variation was imprinted on Siwalik sediments in various modes. Two important proxies, viz. oxygen isotope ratio of soil carbonate and hydrogen isotope ratio of pedogenic clay minerals (both bearing the signature of rainfall) were used to detect if there was any variation in the monsoonal rainfall.

Our results on rainfall variation for the last 11 Myr show that the evolution of monsoon in Indian sub-continent was not smooth. The rainfall was intense at around 10, 6 and 3 Ma. During these periods, the rainfall was at least 3 times higher than the present day amount. Other proxies from Siwalik basin investigated before support these inferences. Net sediment accumulation rate in Siwalik basin at around 10 Ma and 6 Ma increased by factor of 2 to 3. This can be interpreted as increased transportation of weathered material from tectonically active Himalaya by large river systems supported by intense rainfall. Soil characteristics also changed with rainfall variation. Formation of purple and brown color palaeosols with calcareous nodules at around 10 Ma suggests a warm humid climate. The monsoonal rainfall variation record from Siwalik is consistent with record from ocean sediments but the timing does not match exactly with the ocean record probably due to limitation of age determination by palaeomagnetic method.

Weathering in Himalaya caused lowering of CO_2 in atmosphere. Estimation of atmospheric CO_2 from Siwalik palaeosols showed that the CO_2 concentration was about 455 ppmV from 10 to 6 Ma. Before the Himalayan orogeny, the CO_2 concentration fluctuated widely in geological past. For a comparative analysis, CO_2 concentration was also determined from geologically older palaeosols of Gondwana period. CO_2 concentration estimation from Gondwana palaeosols showed that lower Triassic CO_2 concentration was about 255 ppmV and increased up to 1520 ppmV during upper Triassic through an intermediate concentration of 1100 ppmV. During the Jurassic time, the concentration was between 2110 and 2275 ppmV.

Lowering of CO_2 concentration in Mid Siwalik era along with change in rainfall pattern had important impact on vegetation. Pre-Miocene era was dominated by C_3 type of plants. It is seen from Siwalik data that C_4 plants appeared in Late Miocene time. The timing of C_4 plant appearance ranges from 9 to 6 Ma in Indian Siwalik. The nature of vegetational transition from pure C_3 type plants to mixed C_3-C_4 type varies from section to section. In Kangra valley-Haripur Khol section abrupt expansion of C_4 plant was observed at around 6 Ma. In Mohand Rao section, appearance of C_4 plants was observed at around 9 Ma and the transition from pure C_3 to mixed C_3-C_4 was gradual. To reach the maximum abundance of C_4 plants it took around 2 Myr in Mohand Rao section. In all these studies, the age values were determined by palaeomagnetic method with its inherent limitations as discussed before.

In Kangra valley-Haripur Khol section, appearance of C_4 plants at 6 Ma nearly coincides with period of monsoon intensification. This may indicate that appearance of C_4 plants is probably related to joint effects of increase in monsoonal strength (monsoon induced seasonality) and lowering of CO_2 in atmosphere. This follows from the observation that C_4 plants are favored in strongly seasonal climate and it has some physiological advantages over C_3 plants in low CO_2 concentration. Before the appearance of C_4 plants, the CO_2 concentration (estimated from Siwalik palaeosols) was about 455 ppmV. This may imply that, for appearance of C_4 plants, the CO_2 concentration should probably be less than 455 ppmV.

Vegetational reconstruction from Pakistan Siwalik by earlier workers (Quade et al., 1989) 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. 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 vegetation was dominated by C_3 plants up to 6 Ma. Abrupt change in vegetation from pure C_3 to mixed C_3-C_4 vegetation occurred after 6 Ma. In Kangra Valley-Haripur Khol section intensification of rainfall (monsoon) was observed at around 10.5 Ma and 5.5 Ma. Appearance and expansion of C_4 plants coincided with the second phase of monsoon intensification. In Mohand Rao section, appearance of C_4 plants was observed at around 9 Ma and it took nearly 2 Myr to reach the maximum abundance of C_4 plants. Present day rainfall data (where available) show variations in rainfall amount during southwest monsoon in these sections. The difference in the amount of rainfall in these sections suggest that climatic conditions were probably different in them and this might have played an important role in controlling the timing and nature of change in vegetation.

In a mixed C_3–C_4 environment, one can estimate the relative abundance of C_4 plants based on $\delta^{13}C$ of soil carbonate as well as $\delta^{13}C$ of residual organic matter in soil. Our study shows that these two estimates may differ. Assuming that soil carbonate is derived exclusively from plant–respiration, this difference may be due to different respiration rates of these two types of plants (C_3 and C_4) during the growing season. The abundance estimate based on $\delta^{13}C$ of soil carbonate would, therefore, change if the growing season differs from time to time in response to climate fluctuations. Consequently, the difference in $\delta^{13}C$ of soil carbonate and organic matter provide a unique way to decipher climatic change.

Study of chemical diagenesis of sandstones showed that meteoric water has played a major role in determining the oxygen isotope ratio of calcite cement in sandstone. Clay mineral assemblages show illitization of smectite with increase in depth due to diagenesis. Abundance of K-feldspar also decreases with depth, which is consistent with the illitization of smectite. The K-feldspar might have acted as a supplier of potassium during illitization process.

8.2 Future Studies

8.2a Reconstruction of relative abundance of C_3 and C_4 grasses

Reconstruction of vegetational change from pure C_3 to mixed C_3-C_4 plants has been done from the carbon isotope ratios of soil carbonates, tooth enamel, leaf waxes and early diagenetic carbonate cement of sandstone (Quade et al., 1989, 1995; Freeman and Colarusso, 2001; Quade and Roe, 1999; Sanyal et al., 2004a,b). However, carbon isotope ratio of these proxies cannot differentiate C_3 grasses from trees and shrubs. As a result the abundance of C_3 versus C_4 grasses in Siwalik is not known. Understanding of evolution of both the grasses is important as the relative proportions of C_3 and C_4 grasses growing at a site is determined by climatic condition. For example, minimum summer temperature and lower moisture favors C_4 grass (Kelly et al., 1991b).

Reconstruction of grasses can be done from the carbon isotope ratio of organic matter occluded within phytoliths. Phytoliths are microscopic opaline bodies that occur in stems, leaves and roots of plants. During transpiration, along with ground water plants carry silica as monosilicic acid and deposit it in plant cell wall, eventually forming bodies composed of opaline silica. Following the decay or burning of organic tissues, phytoliths are released back into the soil, preserving record of vegetation. Grasses produce large quantities of very distinctive, densely silicified, short-celled phytoliths. Trees and shrubs on the other hand produce significantly fewer, less densely silicified phytoliths in a variety of shapes that are more susceptible to breakage and dissolution (Knoepp et al., 1998).

To quantify the abundance of C_3 and C_4 grasses from phytolith, it is important to characterize the $\delta^{13}C$ value of phytoliths from C_3 and C_4 grasses. It is seen that in the process of phytolith formation and its incorporation into soil, the carbon isotope ratio of phytolith organic matter can be modified in the following ways (Kelly et al., 1991b):

1) **Modification of carbon isotope ratio during formation of phytoliths**: Phytoliths from modern C_3 and C_4 grasses exhibit different carbon isotope ratio relative to that of whole plant tissue (Fig.8.1). This difference may be due to incorporation of ^{13}C-depleted components such as lipid or lignin in phytolith organic matter. The depletion of heavy

isotope in phytolith is more in C_4 plants (9‰) than in C_3 plants (5.3‰), indicating higher concentration of lipids and lignin in C_4 plants relative to those in C_3 plants (Kelly et al., 1991b).

2) Modification of carbon isotope ratio during pedogenesis: Carbon isotope ratio of fresh phytoliths is not same as that of soil phytoliths, which are enriched compared to their fresh counterparts. The enrichment could be due to removal of some lipid fraction during pedogenesis (Kelly et al., 1991b). However, calculation showed that to make the observed enrichment, 90% of the organic matter should be removed which is quite unrealistic. Another possibility is preferential preservation of phytoliths that originate in tissues that are lipid poor relative to lipid rich phytoliths extracted from fresh leaves. The carbon isotope ratio of fresh phytoliths from C_3 and C_4 plants are fixed at −26.8‰ and −15.3‰ respectively. After doing corrections for the above enrichment factor, phytolith isotope data can be used to determine the abundance of C_3 and C_4 grasses through mass

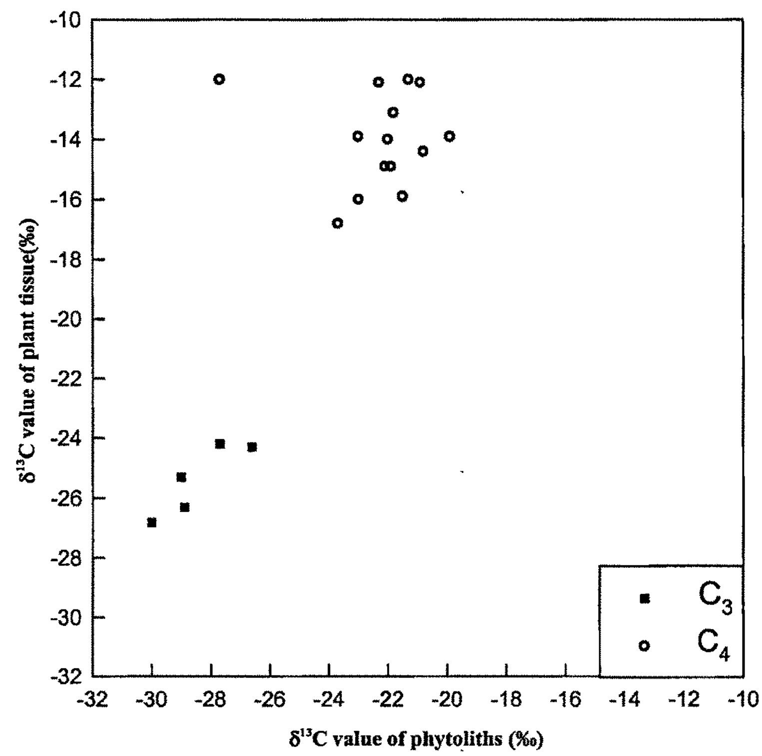

Fig.8.1 *Relation between carbon isotope ratio of fresh phytoliths and plant tissue. The figure shows that carbon isotope ratio of phytoliths is depleted compared to the plant tissue.*

balance.

8.2b Sr isotope ratio in soil carbonate

Sr isotope ratio record from ocean sediments show steady increase in $^{87}Sr/^{86}Sr$ ratio during late Cenozoic period. The rise in Sr ratio was attributed to draining of weathered material from Himalaya, which contains both radiogenic $^{87}Sr/^{86}Sr$ ratios and high Sr (Hodell et al., 1989; Richter et al., 1992). Weathering of sediments, in turn, is controlled by several factors like climate and source rock composition.

Oxygen isotope ratio of soil carbonates from different Siwalik sections shows climatic change in the form of intensification of monsoon at around 10.5, 6 and 3 Ma (Sanyal et al., 2004a). If climate had played a major role in weathering, $^{87}Sr/^{86}Sr$ ratio in contemporaneous river water for the above mentioned periods should be elevated as wet summer (monsoonal) conditions enhances weathering. On the other hand, if Sr isotope ratio is controlled by source rock composition then the variation of $^{87}Sr/^{86}Sr$ in the weathering product will be independent of timing of climate change. This issue could be checked from Sr isotope ratio of soil carbonate, early diagenetic carbonate cement and clay minerals as these bear the signature of river water.

8.2c Ar-Ar dating of ash bed

Age of Siwalik sediments was determined by palaeomagnetic method. In this dating technique magnetic polarity events were constructed from iron oxides, which preserve in situ records of contemporary depositional/crystallization remanence magnetization caused by earth's magnetic field. The magnetic polarity events obtained from sequentially arranged rock succession were correlated with standard geomagnetic polarity time scale (GPTS) and conversion to absolute age was done through tie points. The tie points that have been used for dating Indian Siwalik sequences are age of fossils, matching of the reversal patterns with GPTS. However, best correlation with the GPTS can only be made with tie points of known "absolute age". Presence of ash bed in stratigraphic succession can serve this purpose. Ash bed contains mica, which are considered to be cogenetic with ash falls and should, therefore, date the eruptive events and contemporaneous sedimentation.

Three ash bed samples have been discovered from Indian Siwalik by earlier workers (Sangode et al., 1995; Tandan and Kumar, 1984); one from Haripur Khol section of Himachal Pradesh and two from Ghaggar section of Punjab. Stratigraphic positions of these ash beds show approximate age between 2 to 3 Ma (Tandon and Kumar, 1984; Sangode et al., 1996). Fission track dating of Zircon separated from Ghaggar section ash bed showed that the age of corresponding bed is around 2.5 Ma (Mehta et al., 1993). However, the age obtained in this method was associated with large error (±0.5 Ma,). Ar-Ar dating of mica associated with this ash bed will provide a strong control to constrain the depositional age of the Siwalik sediments.