CHAPTER-IV

Clay Mineral Records of Sediment Cores: Provenance and Paleomonsoon
4.1. Introduction

Clay minerals are the weathering products of rocks and soils and their composition largely depends on climate, geology and topography of the area. Once formed in weathering profiles, clay minerals are eroded, carried away by transporting agents such as river, glacier and wind, and accumulate in sedimentary basins on land or in marine environment.

Clay minerals represent the most ubiquitous components of sediments, fluvial to marine environments. The production, supply and composition of clay minerals in the marine environment largely depend on geology and drainage of the hinterland area, and climate variations (Weaver, 1989; Chamley, 1989). The nature and composition of clay minerals will provide valuable information regarding the type and intensity of weathering on land. It has been demonstrated that clay mineral assemblages in marine sediments are particularly informative as to sources of the sediments, especially in relation to the integral effect of provenance, lithology and climate (Naidu and Mowatt, 1983; Chamley, 1989). Several studies have suggested that the temporal variation of clay minerals in marine sediments can be utilized as paleoclimatic proxies (Sirocko and Lange, 1991; Gingele, 1996; Thamban et al., 2002). Clay mineral distribution patterns in oceans can offer potentially useful proxy data on long term dispersal of water masses and associated pollutants.

Distribution of clay minerals in oceans is complicated by various processes viz., circulation patterns, supply of sediment from multiple sources, size sorting, flocculation and organo-mineral interactions (Grim, 1968; Gibbs, 1977; Kolla et al., 1981). In the marine environment, where the terrestrial input is dominant, the down core variation in sediment characteristics may reveal changes in the intensity of weathering or variations in depositional conditions depending on climatic conditions and/or sea level changes (Kolla, 1981). Therefore, the study of clay minerals is considered to be a reliable tool for the reconstruction of paleoenvironmental conditions in the region.

Numerous studies have indicated the following: (a) Clay minerals in the marine environment are largely detrital (Biscaye, 1965); (b) There are no diagenetic effects in recent marine clays and therefore the provenance of different clay minerals
can be identified (Grim, 1968); (c) Crystallinity of particular clay minerals can also be used as an evidence of climatic change (Jacobs and Hays, 1972); (d) As rainfall is the most controlling factor determining the leaching rates in weathering profiles, the composition of clay minerals in the sediments are useful indicators of paleoclimatic conditions (Singer, 1984).

Most oceanic basins reflect the existence of various controls on the distribution of terrigenous clays. The climate, land petrography, and near shore hydrodynamic constraints intervenes dominantly in turn, depending on the location of the different parts of a given basin. In addition the long distance transportation processes by marine currents and by the wind may strongly modify the distribution of detrital assemblages with respect to the terrestrial production zone. Some in situ formations of clay and associated species occur in certain basins, and complicate the final distribution of mineral suites on the sea floor.

The clay mineral distribution in the western Indian Ocean is largely influenced by the climate and the land geology, but is also controlled by physiographic patterns, sub-marine volcanism and marine currents (Kolla et al., 1976). Quartz- smectite rich clays occur along the Indian margin, south of the Indus River; they result from the climate, weathering of Deccan basalts and are associated with quartz derived from Pre-Cambrian metamorphic rocks, and appear to be primarily dispersed southerly, and to some extent northerly, by surface currents.

Detrital fine grained sediments are abundant both on the shelf and continental slope of the west coast of India. They occur largely as clay minerals, weathered from the rocks of the hinterland and are primarily transported by rivers. The parent rocks in the drainage basins of the rivers have, however been extensively lateritised. Rivers are the principal agents of transport of detrital sediments in to the eastern Arabian Sea. The Indus River is the largest one, bringing enormous amounts of sediment (Haq and Milliman, 1984). Clay particles supplied from land to sea often experience further transportation through long shore and density currents or through reworking processes. The variable influence of long shore currents that strongly depend on meteorologic and seasonal conditions also interferes with the slow and progressive settling phenomena.
Studies on clay mineral composition in the western continental margin of India were mainly focused on the surficial sediments to understand the provenance and transport pathways of fine grained land derived sediments (Kolla et al., 1981; Nair et al., 1982; Rao et al., 1983; Narayana and Pandarinath, 1991; Rao, 1991; Rao and Rao, 1995; Chauhan and Gujar, 1996) and studies on sediment cores were few (Sirocko and Lange, 1991; Chauhan et al., 2000; Thamban et al., 2002, Kessarkar et al., 2003). The clay size fraction of the Arabian Sea lithogenic sediments is derived from a mixture of river run-off from India and eolian dust contributions from Arabia, Pakistan and northern India (Kolla et al., 1981; Naidu et al., 1985). The maximum of clay sedimentation off southwest coast of India is corroborated by both concentration values and accumulation rates and can be attributed to high abundances of fine grained river borne sediments along the southern Indian coast (Naidu et al., 1985). Most of the clay minerals are ubiquitous in the Arabian Sea and could not be related to specific source areas and transport pathways, but the large amounts of smectite off southern India are clearly derived from Indian rivers (Sirocko and Lange, 1991). Clay minerals consist of hydrous layer silicates that constitute a large part of the family of phyllosilicates.

The fine grained clastic fractions, mainly of clay minerals, in the marine environment are the weathering products of rocks and soils on land. Several studies have suggested that the temporal variations of clay minerals in marine sediments can be utilized as paleoclimatic proxies, provided that they are detrital and have not been subjected to alteration by diagenesis (Sirocko and Lange, 1991; Gingele, 1996; Vanderavero et al., 1999). Diagenetic modifications of the detrital clay minerals in marine environment during the recent past are considered to be negligible (Grim, 1968; Chamley, 1997).

Previous studies on clay mineral composition of sediments from the eastern Arabian Sea were mainly based on surficial sediments to understand the provenance and transport pathways of fine grained terrigenous sediments (Kolla et al., 1981; Nair et al., 1982; Konta, 1985; Rao, 1991; Chauhan, 1994; Rao and Rao, 1995). The studies on clay mineralogy of sediment cores in the Arabian Sea and their utility as paleoclimatic proxies are very few (Kolla et al., 1981; Sirocko et al., 1993; Thamban et al., 2002; Kessarkar et al., 2003).
In the present study, clay mineral distribution patterns since Last Glacial Maximum (LGM) in three gravity cores are discussed. The ratios of clay mineral assemblages and their relative abundance were utilized to interpret the plaeoenvironment and paleomonsoon record. The main focus of this chapter is to understand the provenance and to infer paleoclimate and paleomonsoon during late Quaternary.

4.2. Clay mineral abundance

The clay mineral types and the proportions of the individual clay minerals in marine sediments, therefore, depend on the climatic conditions on land and on the nature of the source rocks. The distribution of different clay minerals in the present-day oceans reveals a zonation that strongly reflects the pedogenic zonation and climatic conditions on the adjacent continental land masses (Biscaye, 1965; Griffin et al., 1968; Lisitzin, 1972; Windom, 1976). Clay mineral assemblages in marine sedimentary sequences are, therefore, useful tools for reconstructing the paleoclimate through time. Clay minerals are also being useful for deciphering and reconstructing the sedimentary processes.

Smectite is derived from chemical weathering of parent alumino silicates and ferromagnesian silicates under warm and humid conditions, and also from chemical weathering of basaltic rocks. Kaolinite is readily found in soils of inter tropical land masses characterised by a warm, humid climate, and therefore displays a strong climatic dependence controlled by the intensity of continental hydrolysis (Chamley, 1989). Kaolinite is common on steep slopes within the drainage basin, where there are good drainage conditions. The detrital chlorite mainly results from the chemical weathering of plutonic and metamorphic rocks. The presence of illite and chlorite which reflect the decrease of hydrolytic processes in continental weathering and an increase of direct rock erosion under cold and arid climatic conditions. In addition, illite could also be formed by the weathering of non-layer silicate, such as feldspar from granites under moderate hydrolysis conditions, and by the degradation of micas.

Smectite is considered as settling preferentially in areas of decreased current and associated grain sorting. The variable influence of long shore currents that strongly depend on meteorologic and seasonal conditions also interferes with the slow and progressive settling phenomena. The ability of smectite minerals to settle
preferentially allows identification of current activity (Chamley, 1989, p.120). The relative abundance of smectite displays a distribution that does not parallel the zonal distribution of main weathering processes. This indicates the accessory control of climate, and the dominance of other allochthonous and/or autochthonous processes. The increased amounts of marine smectite recorded off the temperate to sub-arid regions suggest that the mineral partly reflects conditions intermediate between those of cold-dry and warm-humid climate.

The distribution of kaolinite in marine sediment reflects warm, humid climate control and, hence kaolinite is called "low latitude mineral" (Griffin et al., 1968). Kaolinite abundance increases towards the equatorial regions in all ocean basins, and therefore expresses a strong climatic dependence controlled by the intensity of the continental hydrolysis. Marine kaolinite derived from inter tropical soils is generally associated with abundant iron oxides (mainly goethite and sub-amorphous components), and often with gibbsite (Biscaye, 1965). A decrease in kaolinite abundance with increased distance from coast in Indian Ocean sediments is envisaged as conditions of marine transportation (Gorbunova, 1962).

The distribution of chlorite in marine sediments typically reflects high latitude climatic conditions. The relative abundance of illite tends to increase towards high latitudes parallel to chlorite, which reflect the decrease of hydrolytic processes and the increase of direct rock erosion under cold climatic conditions. In addition, abundant detrital illite characterizes the oceanic areas that are linked to either to high altitude cold climate regions like the Himalayas or to desert climate regions.

A detailed study in the Arabian Sea by Kolla et al. (1981) had lead to identify the role of climate, petrographic sources, and currents on the distribution of clay minerals and quartz. Smectite rich clays occur along the Indian margin south of the Indus river; they result from the chemical weathering of Deccan basalt traps, are associated with quartz issued from local Pre-Cambrian metamorphic rocks, and appear to be primarily transported southerly by surface currents. Illite rich clays dominate in most of the rest of the Arabian Sea.

The transportation agents appear to consist of surface currents and turbidity currents off the Indus river area, and mainly of winds in other areas. The effect of arid to desert climate in the northern and western areas favours the dominant control of
land petrography on detrital associations as well as the essential action of wind. In the southern and southeastern region, kaolinite rich sediments probably derive from intertropical soils of Africa, Madagascar and southern India.

Based on the studies of cores from the eastern Arabian Sea, Aoki and Sudo (1973) reported an increase in relative abundance of smectite and kaolinite during interglacial stages, while glacial stage sediments are relatively enriched in illite and chlorite; these clay mineral variations are attributed to changes in the degree of continental hydrolysis, interglacial stages favouring weathering processes on Asian land masses. Under tropical humid latitudes where kaolinite forms abundantly in well-drained soils during both glacial and interglacial periods, the variations recorded in the composition of terrigenous clay input may reflect temporary changes in the intensity and geographic location of rainfall.

The clay minerals present in the sediment cores of the study area in the decreasing order of abundance are - smectite, kaolinite, illite and chlorite. X-ray Diffractograms of some selected samples are shown in Figures 4.1–4.3. The relative abundance of clay minerals varied significantly with in the cores and among the cores and is described in detail in the upcoming section.

Figure 4.1. X-ray diffractograms of some samples at different core depths of the core AAS38-4.
Figure 4.2. X-ray diffractograms of some samples at different core depths of the core AAS38-5.

Figure 4.3. X-ray diffractograms of some samples at different core depths of the core SK145B/C-8.
Core AAS 38-4

Smectite, illite, kaolinite and chlorite are the dominant clay minerals in the decreasing order of abundance on the upper slope region, where the core AAS 38-4 is located. Smectite varies from 23-68% with an average of 52%. Illite content varies from 10-32% with an average of 21%. Kaolinite percentage varies from 10-26% with an average of 18%. Chlorite percentage varies from 4-15% with an average of 8% (Fig. 4.4).

Figure 4.4. Pie diagram showing the relative abundance of clay minerals - smectite, illite, kaolinite and chlorite - at different core lengths in the core AAS 38-4.

Core AAS 38-5

The abundance and distribution of clay minerals in core AAS 38-5 (located in deep waters) is similar to that of core AAS 38-4. Smectite, illite, kaolinite and chlorite are the dominant clay minerals in the decreasing order of abundance in the deeper slope region i.e., at the core site AAS 38-5. Smectite percentage varies from 33 to 70% with an average of 55%. Illite content ranges between 8 and 28% with an
average of 18%. Kaolinite content varies from 10–26 % with an average of 17%. Chlorite content ranges from 5 to 20% with an average of 11% (Fig. 4.5).

Core SK 145B/C-8

In core SK 145B/C-8, although smectite is the dominant mineral, the order of abundance of other clay minerals varies. Smectite is followed by kaolinite and illite in abundance, which is contrary to clay mineral variations of core AAS 38-4 and AAS 38-5. In this core the second abundant clay mineral is kaolinite whereas in other two cores illite was second abundant. As observed in other two cores, in this core also very high smectite content is recorded and it ranges from 29 -73 % with an average of 59 %. Kaolinite varies from 7 -47 % with an average of 20 %; the relative abundance of illite varies from 7-29 % with an average of 18% (Fig. 4.6).

It is interesting to note that chlorite is almost absent through out the core length, except at a few randomly distributed horizons. In top, middle and bottom portion of the core chlorite is almost absent.
4.3. Temporal distribution of clay minerals

Core AAS 38-4

At the core site AAS 38-4, smectite content is more (~ 60 %) during 0-4 ka BP, whereas during 4.2-6.6 ka BP it decreased to 47 % (Fig. 4.7). During 6.8-9.2 ka BP an increase of (~52 %) in smectite content is recorded, and again decreased to ~45% during 9.7 -14 ka BP. An increase (to 60 %) in smectite content is recorded during 15-19.4 ka BP (Fig.4.7). Illite content is ~10 % and ~15 % during 0-3.5 ka BP and 3.5-5.6 ka BP respectively. Illite increases in relative abundance up to 31% during 5.9-14 ka BP, whereas gradual decrease (~ 11 %) is observed during 15-19.4 ka BP (Fig.4.7).
Figure 4.7. Temporal distribution of smectite, illite, kaolinite and chlorite in the core AAS 38-4.

The relative abundance of kaolinite is higher (~20%) during 0-3.3 ka BP and it is about 15% during 3.5 - 4 ka BP. During 4.2 - 15 ka BP kaolinite content is about 23%, whereas during 16 - 17.4 ka BP it decreases to ~12%. Again kaolinite abundance increases to 20% during 18 - 19.4 ka BP (Fig.4.7). Chlorite content is more (~12%) whereas during 0-5.3 ka BP and is 8% during 5.6-16.3 ka BP. During 17-19.4 ka BP, chlorite content further decreases to 6% (Fig. 4.7).

Core AAS 38-5

In core AAS 38-5 also smectite is the dominant one followed by illite, kaolinite and chlorite (Fig. 4.8). During 0-2.8 ka BP the smectite content is more (~55%), whereas during 3.1-3.3 ka BP it is less (~30%). The abundance of smectite is very high (~65%) during 3.6-8 ka BP and during 8-13 ka BP it decreased to about 55%. During 13. 5-15.5 ka BP smectite increases upto 70% and during 16-16.7 ka
BP it decreased to 44%. An increase of smectite to 60% during the period 16.7-17.4 ka BP is recorded (Fig. 4.8).

![Graph of Temporal distribution of smectite, illite, kaolinite, and chlorite in the core AAS38-5.]

During 0-3.3 ka BP, illite content progressively increases from 8 to 27%, while it decreases to 10% during 3.6-4 ka BP. At 4.5 ka BP the illite content shows a rapid increase up to 39%. This might be an outlier. A gradual decrease (from 20-8%) in illite content is observed during 4.8-7.8 ka BP, while 32% of illite is recorded during 8-9 ka BP. During 13.5-16.5 ka BP, illite content is about 10%, and it gradually increases to 30% at 17 ka BP (Fig. 4.8).

Kaolinite content is slightly higher (22%) and low (15%) during 2-5 ka BP and 4-8 ka BP respectively. Further it slightly increases to 18% during 8-15 ka BP. About 10% of kaolinite was recorded during 14-17.5 ka BP (Fig. 4.8).

Chlorite content is very low (8%) during 0-3 ka BP, but it increased to 20% around 3 ka BP. The chlorite abundance is of 12% during 4-5 ka BP and about 10%
during 7-8 ka BP. From 8 to 17 ka BP the chlorite content varies in cyclicity with increasing and decreasing order and ranges between 8-16 % (Fig. 4.8).

**Core SK 145B/C-8**

In this core also smectite content is higher like in other two cores. Smectite content is uniformly higher (~65 %) from 0-14 ka BP, whereas during 15-18.7 ka BP it gradually decreases (to 50 %) (Fig. 4.9).

![Graph of smectite, illite, kaolinite, and chlorite in core SK 145B/C-8](image)

Figure 4.9. Temporal distribution of smectite, illite, kaolinite and chlorite in the core SK 145B/C-8.

Illite also varies significantly throughout this core. It is comparatively less (~17 %) on the core top representing 0-5 ka BP, whereas during 5-13 ka BP an increase (~22 %) in illite content is recorded. A decrease (20-11 %) in illite content is recorded during 13-14 ka BP, and it increases (to 23 %) during 15-17.4 ka BP. Further, a decrease (to 13 %) of illite is recorded during 18-18.7 ka BP (Fig. 4.9).

At this core site kaolinite is the second dominant mineral and it varies throughout the core. Kaolinite content is more at the core top (~25 %) representing 0-4 ka BP.
During 4-13.5 ka BP a decrease (to 18 %) in kaolinite content is recorded, whereas during 14–18.7 ka BP an increase (to 35 %) in kaolinite content is recorded (Fig. 4.9).

It is interesting to note that chlorite is almost absent throughout the core length, except at few core depths representing 4-6 ka BP, 8-9 ka BP, 11-12 ka BP, 13-14 ka BP and 16-17 ka BP where a small amount of chlorite is observed (Fig. 4.9).

4.4. Clay mineral ratios

Clay mineral ratios are extensively employed to decipher the climatic conditions of the region. The ratios of clay minerals rather than individual abundances will help to eliminate the effect of mutual dilution on clay mineral assemblages. Since kaolinite is formed under warm humid conditions and chlorite and illite under arid to cold climate, an increase in the ratio of kaolinite/chlorite and kaolinite/illite may indicate enhanced humidity.

Clay mineral ratios - kaolinite/chlorite (K/C), kaolinite/illite (K/I) and chlorite/illite (C/I) are shown in Figures 4.10, 4.11 and 4.12.

![Figure 4.10. Temporal distribution of kaolinite and chlorite ratios in the cores.](image-url)
Figure 4.11. Temporal distribution of kaolinite and illite ratios in the cores.

Figure 4.12. Temporal distribution of chlorite and illite ratios in the cores.
**Kaolinite /Chlorite (K/C) ratio:**

In core AAS 38-4, K/C ratios, in general, range from 1 to 4.5 (Fig. 4.10). K/C ratios range between 1 and 2 during 0–5 ka BP. During 5.5–11 ka BP K/C ratios range from 2.5 to 4.5 and during 11–14 ka BP the ratio is just around 2. The ratios decrease from 4.5 to 2 during 14–17 ka BP and during 17–19.4 ka BP the ratio is around 3 in the core AAS 38-4 (Fig. 4.10).

In core AAS 38-5, K/C ratio is 3 during 0–3 ka BP and the ratio varies from 1 to 2 during 3–12 ka BP. Both increasing and decreasing trends ranging from 1 to 3 were recorded during 12–18 ka BP in the core AAS 38-5 (Fig. 4.10).

In core SK 145 B/C-8, as chlorite content is zero, most of the samples during different time intervals exhibit K/C ratios as zero. Because of this, the trend of K/C ratio cannot be explained with a definite conclusiveness in the core SK 145 B/C-8 (Fig. 4.10).

**Kaolinite/Illite (K/I) ratio:**

In general, the core AAS 38-4 exhibits high (1-1.5) K/I ratio during late Holocene (0–5.5 ka BP); the ratio is ~1 during 6–8 ka BP and during 8–17 ka BP, K/I ratio is <1 (0.5-1). K/I ratio increased from 0.5 to 1.5 during 17–19 ka BP in core AAS 38-4 (Fig. 4.11).

In core AAS 38-5, K/I ratios range from 0.5-2.5. The ratios are ~2 and 0.5 during 0–2 ka BP and at 3 ka BP respectively. It gradually decreases from 2 to 0.5 during 3–4 ka BP, and increases from 0.5 to 1.5 during 4-7 ka BP. The ratio ranges around 0.5 during 8-13 ka BP and increases to 1.5 at 13.5 ka BP. It gradually decreases from 1.5-0.5 during 13.5-17.4 ka BP (Fig. 4.11).

In core SK 145B/C-8 also, K/I ratio generally range from 0.5-2.5. K/I ratio is around 1 during 2-13.5 ka BP. It shows increasing trend (up to 3) during 13.5-18 ka BP (Fig. 4.11).

**Chlorite/Illite (C/I) ratio:**

Chlorite/illite ratios in core AAS 38-4 range from 0.2 to 1.2. It is about 0.8 during 1 -5 ka BP and it gradually reduces from 0.8 to 0.2 during 5 -6 ka BP. The
ratio is around 0.2 and 0.4 during 6–16 ka BP and 16–19.4 ka BP respectively in the core AAS 38-4 (Fig. 4.12).

In core AAS 38-5, C/I ratio is about 0.8 during 0–6 ka BP. During 6.5–8 ka BP C/I ratio gradually reduces from 1.6 to 0.4. The ratio varies from 0.4 to 0.8 during 8–17.4 ka BP in the core AAS 38-5 (Fig. 4.12).

In core SK 145 B/C-8, C/I ratio also behaves similar to that of K/C ratio, as chlorite content is zero. The C/I ratio is zero throughout the geological time span of the sediment column (Fig. 4.12).

4.5. Provenance

Clay mineral characteristics of the aquatic sediments reflect the prevailing climatic conditions, hydrography, geology and topography of the continental source area (Chamley, 1989). The variations in clay mineral abundances, therefore, are a tool for deciphering the sediment sources and transport pathways to an area. Clay minerals in the marine environment are found to be largely detrital and widely dispersed (Biscaye, 1965). Since the clay minerals are ubiquitous in the marine sediments and their measurement is relatively easier and economic than the other sophisticated techniques, they provide a potential tool for paleoclimatic reconstruction. Presuming that the geology and geomorphology of the source region remained fairly stable for the time period in consideration in a tropical region, rainfall seems to be the main factor determining the composition of clay minerals in the marine sediments (Singer, 1984; Chamley, 1989; Thamban et al., 2002). Clay mineral composition basically indicates the intensity of weathering, especially the degree of hydrolysis, at source rock regions that can be used as paleoclimatic indicators (Chamley, 1989). Diagenetic effects on different clay minerals are considered to be insignificant and therefore the provenance of different clay minerals can be identified (Grim, 1968). Nevertheless a cautious approach is warranted as many other processes are acting upon clay minerals simultaneously or immediately after reaching the marine environment, suppressing the climate induced differentiation of clay minerals. These processes include size sorting of clay minerals during transportation (Gibbs, 1977), flocculation at lower salinities (Grim, 1968), selective deposition of certain clay minerals in relation to organo-mineral interactions (Degens and Ittekot, 1984), texture related clay mineral variations (Maldonado and Stanley, 1981), dispersal of clay minerals due to the
prevailing of regional and local currents (Kolla et al., 1981; Naidu et al., 1985), redistribution of settled clays during reworking (Biscaye, 1965). As a consequence of these factors, selective transportation, deposition or mixing of clay minerals from different sources takes place.

Clay mineral distribution in the surficial sediments along the western margin of India indicates three different sources: (i) Himalayan source in the north characterised by high illite and chlorite that are transported mainly by Indus river, (ii) a Deccan Trap source in the central region characterised by abundant smectites which are the erosion products of basic volcanic rocks of central India, and (iii) a gneissic province characterised by high kaolinite and gibbsite that are the weathering products of Precambrian gneissic rocks and laterites of southern India (Rao and Rao, 1995).

Smectite occurs along the Indian margin south of the Indus river, which resulted from the weathering of Deccan trap basalts, and appear to be primarily dispersed towards south by surface currents. In the southern most part of the Indian margin, kaolinite rich sediments probably derive from tropical soils of southern India, and are mainly distributed by north equatorial currents. The Himalayan source of clay minerals and their possible transport by the Indus river to the present study area can be ruled out, as the influence of Indus river on the shelf sedimentation is largely limited to the north of Gulf of Kachchh because of the presence of macro tidal currents, which act as barrier for longshore sediment transport to the south (Nair et al., 1982). High smectite and relatively low illite and chlorite values are characteristic of the clay minerals in the study area. Low concentrations of illite were also recorded in sediment cores from the continental slope of southern India by Sirocko and Lange (1991). Abundance of smectite in present study area suggests its derivation from the erosion products of basic volcanic rocks from central India under a semi-arid climate, and transported southward in the shelf and slope regions during the southwest monsoon because of strong southward currents. Further, the smectite might have also been derived from the submerged basic volcanic rocks in the continental shelf and slope regions and in the Lakshadweep area of southwest coast of India.

Similar to the results of present study, Rao et al. (1983) and Rao and Rao (1995) have also recorded smectite, kaolinite and illite in the decreasing order of abundance in the surficial sediments of the continental shelf and slope off
southwestern India. But Thamban et al. (2002) have observed kaolinite, illite, smectite, and chlorite in order of decreasing abundance and opine that higher amounts of kaolinite and illite clearly reflected their derivation from the hinterland, which consists mainly of Precambrian crystalline rocks. Intense chemical weathering and leaching of crystalline rocks under the tropical humid climates leads to the formation of mainly kaolinite and gibbsite (Chamley, 1989). It is suggested that high kaolinite in sediments of the upper continental slope of southwest India is due to the supply from hinterland source rocks and cross-shelf transport processes. Kessarkar et al. (2003) argue that low illite and high kaolinite off Cochin may be explained on the position of Western Ghats and the sedimentary formations lying between the coast and the Western Ghats. As the steep cliffs of the Western Ghats are situated on the Quilon–Cape Comorin, it is likely that residual illite and chlorite were released from the gneisses and schists under intense rainfall conditions and subsequently transported and deposited on to the continental slope. Since the Ghats are away from the coast between the Bhatkal and Quilon, the soils between the Ghats and the shore i.e., alluvium and the Warkalli beds, may have been subjected to active hydrolysis and drainage have preferentially released large kaolinite (Kessarkar et al., 2003).

We suggest that variation in distance by a few kilometers between the Western Ghats and the coast may not make much difference in the hydrological processes as the terrain has more or less similar geomorphic feature, except the wide coastal plains off Cochin, and as it experiences similar humid climate and high rainfall all along and undergo similar hydrolysis. Further, the rainfall is higher in the central than the southern segment of Western Ghats. Therefore, in our view, the residual and sedimentary kaolin deposits that occur as 10-20 m thick beds at several places along the southwest coast of India act as major source for kaolinite in the offshore region, apart from laterites and crystalline rocks of hinterland. Further, rhyolites and dacites of acid volcanic rocks that occur in and around St. Mary Islands and in the shelf region of Mangalore area, further north of the study area, might also be contributing for the abundance of kaolinite in the offshore region through the long shore transport of weathered products. It can be suggested that the sediment source of southern India is constantly delivering kaolinite and illite, but the sediment dispersion on the Indian continental slope is controlled by bottom topography, water currents and gravitational deposition. These mechanisms also control the distribution pattern of other clay
components in this area. Smectite and kaolinite accumulation are found to be moderate to high and show only small differences between Glacial and Holocene distribution patterns.

4.6. Paleomonsoon and paleoenvironmental scenario

The climate fluctuations may be the prime controlling factor for the distribution of clay minerals. Several processes such as — size sorting during transportation (Gibbs, 1977), flocculation at low salinities (Grim, 1968), selective deposition of some clay minerals in response to organo-metal interactions (Degens and Ittekkot, 1984), dispersal due to the prevalence of regional and local currents (Kolla et al., 1981) etc. - act on the distribution of clay minerals in the marine environment. As a consequence of these processes, selective deposition or mixing of clay minerals from different sources takes place. Therefore, a proper approach is essential for meaningful climatic interpretations of clay minerals.

Flocculation of clays under changing pH conditions is limited to the coastal ocean and may not be significant in open ocean regions (Thamban et al., 2002). Close association between organic matter and fine-sized clay minerals has been suggested to be of importance in clay mineral concentrations (Degens and Ittekkot, 1984). Although the cores studied in the present work contain high organic matter, it might not have influenced the concentration of smectite as this mineral is mostly derived from the Deccan trap source rocks from the hinterland. Grain size variations also seem to have no relation to the clay mineral content as observed in the down-core variations at all the three core sites. Oceanic currents are good conduits for the transport of fine-grained terrigenous particles within the ocean (Kolla et al., 1981). Based on this, Rao and Rao (1995) suggested that the high illite content along the western continental slope off India might have northern source, and carried by the southerly monsoon currents. But the predominant Al-rich illite in the cores of present study suggests a hinterland origin for the clays along the southwestern margin of India.

The erosion and transportation of soils is climate dependent, which are the main source for the supply of terrigenous clays along the continental margin of India. As the western hinterland of India is characterized by steep slopes with heavy monsoonal rainfall, it is presumed that clays were not stored on land for periods more
than the geological time span discussed in this study. Such a relatively faster terrigenous transport to the ocean is consistent with the higher average sedimentation rates along the western margin of India as reported earlier (Pandarinath et al., 2004 and references therein) and also in the present study.

As the sediments in the study area are mainly detrital, derived from the adjacent hinterland through the rivers, the temporal variations in the sedimentation rates and characteristics reflect the changes in weathering conditions as a result of fluctuations in the intensity of monsoon in the region. Under tropical humid conditions where kaolinite forms abundantly in well-drained soils during both glacial and interglacial periods, the variations recorded in the composition of terrigenous clay input may reflect changes in the intensity of monsoon (Chamley, 1989, p.436). In the Atlantic, off Niger River, abundant supply of kaolinite from about 13,000 to 4500 yr BP suggests very active precipitation over the continental river basin, especially in middle and upstream areas where kaolinite preferentially formed in Cenozoic soils (Pastouret et al., 1978).

The variations of sea level during alternating glacial-interglacial periods may have induced noticeable changes in clay mineral composition derived from river drainage basins or continental shelves. Indirect control of late Quaternary climate on clay assemblages through sea level variations are reported in the literature (e.g. Japan Sea, Oinuma and Aoki, 1977; Behring Sea, Naidu et al., 1982).

The specific clay mineral ratios are employed to infer climatic conditions. Since the kaolinite is formed under warm humid conditions and illite and chlorite under cold to arid conditions, changes in ratios of K/C and K/I serve as indicators of humidity (Chamley, 1989; Vanderveroet et al., 1999). Kaolinite content, and K/C and K/I ratios, which serve as proxies for continental humidity, indicate the distinct events of monsoon intensification. Crystallinity and chemistry of illite provide proxies for the intensity of hydrolysis on land (Chamley, 1989; Gingele, 1996). The characteristic high rainfall and temperature in the coastal Peninsular India would lead to strong hydrolysis of illite.

The last glacial period as recorded in the cores is characterized by significant contribution of physical weathering products, indicating relatively arid conditions prevailed at source regions. Proxies for continued humidity (kaolinite content, K/C
and K/I ratios) seem to indicate that distinct events of monsoon intensification punctuated the generally weak summer monsoon. Based on the records of enhanced values of kaolinite content and K/C ratios during ~22000-19000 yr BP, Thamban et al. (2002) have inferred an intensification of monsoon, and consequently an increased transport of chemically weathered products, during this period, which may indicate an enhanced precipitation related to monsoons and/or sea level fall. However, the summer monsoon activity during Last Glacial Maximum (LGM) was reported to be weak (Duplessy, 1982), and this period corresponds to rapid sea level fall during the late stages of Pleistocene glaciation (Fairbanks, 1992). During the lowered sea level, rivers may have debouched directly on the slope region and consequently they would have contributed hinterland derived weathered products such as kaolinite in enhanced quantities.

A significant increase in hydrolysis and erosion on land that occurred during the early deglaciation suggest a major climatic amelioration (Thamban et al., 2002). Several proxy records from Indian monsoon regime also support such an early deglacial initiation of summer monsoon conditions (Sirocko et al., 1993; Overpeck et al., 1996; Naqvi and Fairbanks, 1996). A steep increase in kaolinite concentration, K/C and K/I ratios during the late deglaciation between 8800 and 6400 yr BP, a period of reduced humid conditions, was recorded by Thamban et al. (2002) and they attributed such increase to enhanced chemical weathering and fluvial inputs. They further observed increased K/C and K/I ratios at about 6400 yr BP and argued that precipitation around this time must have been sufficient enough to evolve perennial river systems, and eroding and transporting the terrigenous materials.

Various studies have reported that the intensity of SW monsoon was high between ~13000 yr BP with a maximum at ~9000 yr BP (Prell, 1984; Van Campo, 1986; Naidu and Malmgren, 1996; Rajagopalan et al., 1997). But Thamban et al. (2002) suggest that the monsoon intensity was low during 13000-9000 yr BP and enhanced precipitation started after 9000 yr BP. They further observed that the relative variations in clay mineral contents and their ratios in the late Holocene suggest a reduced summer monsoon activity since ~5600 yr BP, and this is similar to the observations made by others (Van Campo, 1986; Rajagopalan et al., 1997; Enzel et al., 1999) with regard to paleomonsoon records. However, no such markers could be established in the present study.
The temporal variations documented in clay minerals in the present study show that kaolinite, chlorite and illite levels show an oscillating trend. Smectite levels are constant throughout, kaolinite and chlorite levels are high since 6 ka BP, while illite is higher than both kaolinite and chlorite during 19.5–6.8 ka BP. High ratios of kaolinite/chlorite from 19.5–6.3 ka BP suggest the prevalence of humid conditions. Low K/C ratios since Mid-Holocene to the present indicate reduced monsoonal activity and consequently low weathering rates. Chlorite forms under arid conditions and high chlorite/illite ratio from 6.3 ka BP to the Present provide evidence for the extent of aridity. Generally, illite and chlorite form under dry/arid conditions and kaolinite under humid conditions. The gradual decrease in illite and increase in kaolinite from 17.4 ka BP suggest that the climate has gradually turned to warm humid conditions since then in this region. Based on clay mineral proxies, Gingele et al. (2004) have inferred more humid conditions between 11 and 6 ka BP and the onset of more arid conditions around 5.5 ka BP, which reached a maximum at 3.6 ka BP. It appears that these arid conditions are responsible for the low sediment supply in the last 3 ka in the southwestern margin of India.

Periods of relatively warm water in the sea correlate on land to relatively strong hydrolysis (i.e., high rainfall and temperature), responsible for the degradation of illite, the production of pedogenic kaolinite and smectite. Opposite conditions marked by low rainfall and temperature appear to have prevailed during periods of cold sea water, leading to the preservation on land of pre-existing, rather well-crystallized illite, chlorite and smectite (Chamley, 1989). In addition to clay mineral data, the levels suggesting enhanced hydrolysis on land tend to be enriched in coarse sediment fraction, calcium carbonate and in feldspars. Therefore, the paleoclimate information deduced from clay mineral assemblages in marine sediments basically concerns the degree of hydrolysis at the surface of exposed landmasses. Under tropical humid latitudes where kaolinite forms abundantly in well-drained soils during both glacial and interglacial periods, the variations recorded in the composition of terrigenous clay input may reflect temporary changes in the intensity of rainfall. Abundant supply of kaolinite correlates with very high sedimentation rates, which suggests very active precipitation over the continental river basin (Pastouret et al. 1978). On the other hand, low sedimentation rates correspond to enhanced supply of detrital smectite and chlorite, suggesting either a decrease in the precipitation (i.e.,
dryer climate), or preferential rainfall as observed by Pastouret et al. (1978) on the coastal zones of North-Equatorial Western Africa.

A careful evaluation of the modern distribution and possible factors affecting the clay mineral abundance along the eastern Arabian Sea indicate that the past variations of clay mineral proxies may be used to reconstruct the paleoclimatic conditions on the Indian subcontinent. Since lithogenic sedimentation along the southeastern Arabian Sea is mainly run-off related, the clay minerals would carry signatures of the intensity of hydrolysis on land and the fluvial strength.

Since kaolinite is formed under warm humid conditions and chlorite and illite under arid and cold climate respectively, an increase in the ratio of kaolinite/chlorite and kaolinite/illite may indicate the prevalence of humid climate (Gingele, 1996). During most of the last glacial period, the eustatic sea level remained lower than the present level with a lowest value (~120m) during the LGM (Fairbanks, 1989). Widespread arid conditions (Prell, 1984) in association with the lowered sea level during the LGM would have lead to the enlargement of desert area of the northwestern India and the dust laden coastal plains. Clay mineral data suggest that the illite concentration increased during glacial period. The increased illite and chlorite input and decreased kaolinite concentration could be attributed to an enhanced dust input related to an expanded desert region and reduced fluvial supply during LGM.

4.7. Summary

Clay minerals basically express the intensity of weathering, and especially of hydrolysis, on the land masses adjacent to sedimentary basins. Since the lithogenic sedimentation along the western continental margin of India is mainly attributed to river run-off, the clay fraction should contain signatures of past monsoonal climate on land.

The dominant clay minerals recorded in the sediment cores are smectite, kaolinite, illite and chlorite. Their relative abundance varies significantly within and among the cores. Smectite is the dominant mineral in all the cores followed by illite in upper as well as deeper slope regions, except in one core where kaolinite is the second abundant. There is a distinct variation in abundance during the Holocene and LGM.
The temporal distribution of clay minerals is controlled by the monsoon intensity, hydrolysis, sea level changes and climate of the region. High ratio values of clay minerals, particularly, K/C and K/I suggest strong humid conditions since last glacial period.

Since kaolinite is formed under warm humid conditions and chlorite under semi-arid to arid and cold climate, an increase in the ratio of kaolinite/chlorite may indicate enhanced humidity. Illite forms under cold humid conditions and an increase in chlorite/illite ratio would suggest an arid climate on land. As smectite is formed by intense chemical weathering of hinterland basaltic rocks under semi-arid conditions, increase in smectite/illite ratio should also indicate increased precipitation on hinterland.

Monsoon intensity, southerly coastal currents and humid climate played a major role in the clay mineral distribution and abundance. The study strengthens the idea of employing the clay minerals as proxies to decipher paleomonsoon, paleoclimate and paleoenvironmental conditions during the Late Quaternary.