Holocene Climate Change and Environment

Edited By

Navnith Kumaran

Damodaran Padmalal

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Navnith Kumaran
Formerly of Agharkar Research Institute, India

Damodaran Padmalal
National Centre for Earth Science Studies, India

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CHAPTER

8

Reading source, Holocene climate change and monsoon signatures in surface and core sediments from western Bay of Bengal

Ganapati N. Nayak, Purnima Bejugam, Janhavi Kangane
Marine Sciences, School of Earth, Ocean and Atmospheric Sciences, Goa University, Goa, India

8.1 Introduction

Understanding climate change on Earth is gaining importance as humans are worried about what will happen in the future. Before predicting future climate changes, it is essential to know (a) whether Earth had experienced such changes in the past, and if yes (b) what factors control these changes? The scientific results published in recent years on climate change based on isotope measurements, microfossils and others have largely answered the first question and proved that Earth has experienced climate change in the past (Ahmad et al., 2008; Rashid et al., 2011; Panchang and Nigam, 2012; Raza et al., 2014; Bejugam and Nayak, 2019a). The beginning of civilizations, settlement of people and societies, the growth of urban settlements and agriculture have all been related to changes in climatic conditions (Singhvi and Kale, 2010), directly or indirectly. In recent times largely on account of the impact of global warming and climate change on food production and lifestyle of the people, understanding climate change has become more important. The main factor is the solar energy that drives Earth's climate. The Earth on an average receives 430 quintillion joules (18 zeros after 430) of energy from the Sun. Solar radiation includes visible light, ultraviolet light, infrared, radio waves, X-rays, and gamma rays. This energy is redistributed within the atmosphere, hydrosphere, lithosphere, and biosphere. The three elements of the Milankovitch (Orbital) cycles, namely eccentricity, obliquity, and precession, contribute to the variation in energy received from the Sun to the Earth and therefore contribute to climate change. The heat or the energy is also added to Earth's surface by volcanic eruptions and heat transfer through conduction and convection within the Earth. Further, the climate of a location is affected by the land topography, elevation, distance from the sea, distance from the equator/polar, the direction of winds, ocean currents, water bodies, vegetation, and precipitation. The Earth's temperature is a balancing act of the radiation budget and higher temperature means that heat waves are likely to occur more often and possibly last longer. Global warming refers to the long-term rise of the planet's temperatures and is an aspect of climate change. It is caused by increased concentrations of greenhouse gases in the atmosphere, mainly from burning fossil fuels, deforestation and the type of farming that is from human activities. Carbon dioxide, a by-product of fossil fuel combustion, is the principal greenhouse gas contributing to global warming along with other gases namely methane, nitrous oxide, and several industrial gases. All these are important contributors to climate change.

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The paleoclimatology is a multidisciplinary subject, includes geology, physics, chemistry, biology, archaeology, and related fields that study earth, ocean, and atmosphere. The Earth has experienced many cold and warm climates in the past and the most recent warm period is referred to as Holocene. The Holocene started after a prolonged Ice Age called Last Glacial Maxima 22–18 kya. The Holocene was a glacial retreat/warming with many short cooler phases and was as follows: (1) 10,000–8500 BC—Younger-Dryas—cold period; (2) 5000–3000 BC—Holocene Optimum/Climatic Optimum—warm period—the average global temperature was maximum, that is, 1–2°C higher than that of today. The great ancient civilizations of the Earth flourished during climate optimum; (3) 3000–2000 BC—cold period—caused a large decrease in sea level; (4) 2000–1500 BC—warm period; (5) 1500–750 BC—cold period; (6) 750–150 BC—warm period; (7) 150 BC–900 AD—cold period—cooling began during the Roman Empire (150 BC–300 AD) but 600–900 AD was referred to as "The Dark Ages" as average global temperatures were extremely low; (8) 1100–1300 AD—the Medieval Warm Period also called Little Climatic Optimum; (9) Up to 1400 AD—a cooler and more extreme weather; (10) 1550–1850 AD—cold period—Little Ice Age (LIA); and (11) From 1900 AD warm period. It is important to note that global average temperatures were less than 1 degree warmer during the Medieval Warm Period and less than 1 degree cooler during the LIA than the temperature of 1900 AD.

The Indian Summer Monsoon (ISM; June–September) involving large exchanges of mass and energy from the ocean, atmosphere, and continents is the strongest climate expression of Earth and the monsoon will change in the face of global warming (Turner and Annamalai, 2012). Saha et al. (1979) stated that the summer monsoon affects the lives of millions of people who are dependent on monsoon rains for agriculture, hydroelectric generation, industrial development, and other basic human needs. Singhvi and Kale (2010) stated that agriculture in India is largely monsoon rainfall dependent and hence it is important to understand the future prediction of monsoon. The pressure gradient created by the solar heating causes cross-equatorial flow and affected by Earth's Coriolis force is responsible for the winds of the southwest (SW) summer monsoon. While blowing from ocean to land these winds pick up moisture from the warm Indian Ocean and bring the ISM or SW monsoon. Around September pressure gradient reversal occurs, the cooler high-pressure air from land starts moving toward the ocean during this period with lower pressure giving rise to the northeast (NE) monsoon. Therefore, the monsoon in the Indian Ocean is due to the shifting of winds seasonally from the SW in summer and the NE in winter. Most parts of India receive rains of the SW monsoon while Tamil Nadu state receives NE monsoon rains. Prell and Kutzbach (1992) and Higginson et al. (2004) have reported that the Indian SW and NE monsoons have changed their relative strengths with time and exhibited a relationship with cold (stadial) and warm (interstadial) events of the North Atlantic. Sirocko et al. (1996), however, related Indian monsoon to ENSO of the Pacific at centennial time scale. The ISM was related to the major global climatic events such as the Roman Warm Period, Medieval Climate Period, and the LIA (Naidu et al., 2020). The weaker ISM was reported during the LIA (Naidu et al., 2020) and the strengthening of the Monsoon during the retreating phase of LIA (Panchang and Nigam, 2012). However, the ISM response to forcing factors and climate variables has not yet been fully explored and understood.

The indirect forms of evidence, for climate-dependent natural processes/parameters, that can be used to infer climate are called proxy. Proxies are stored in different archives namely tree-rings, ice-cores, corals, ocean, or lake sediment cores. The sediment formed by the physical and chemical weathering of rocks present on the Earth's surface is transported through the glacier, air, or water medium and finally deposited. The rivers are carriers of material that include suspended and bed sediments, organic matter and nutrients from land to ocean. The lithogenic and biogenic elements are transferred from the

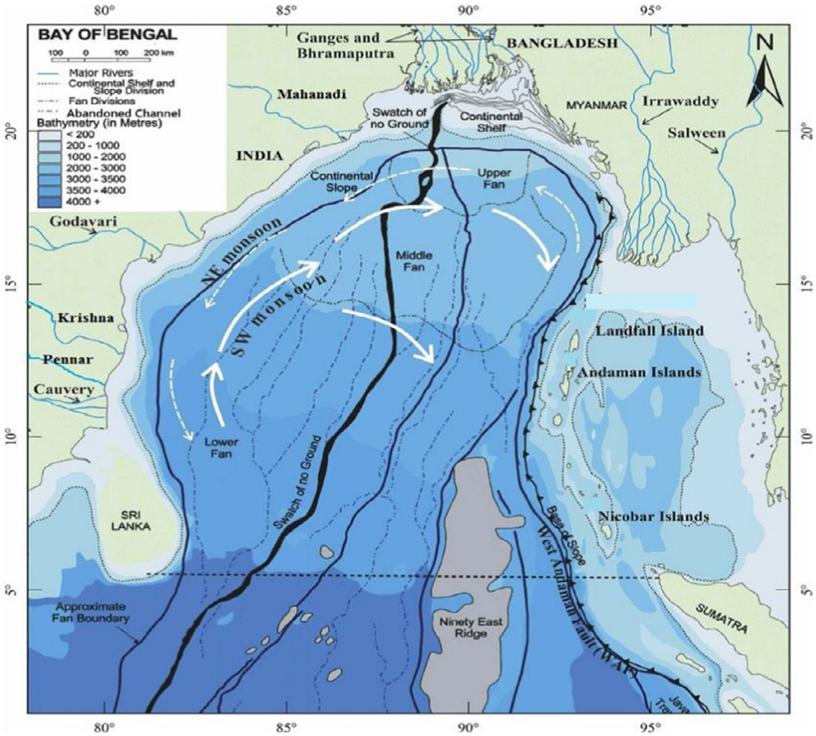

FIGURE 8.1

Seafloor morphology, Bay of Bengal (Bejugam, 2018).

terrestrial environment to the ocean which is the primary connection in their global cycle (Billen, 1993). The rates of sediment deposition depend on parent rock type, weathering activity, topography, the rate of sediment flux, tidal activity, pH conditions, biological activity, and environmental conditions (Xu et al., 2011; Tripathi, 2017). The sediment texture, diatoms, foraminifera, pollen, ice cores, tree rings, isotope geochemistry, the concentration of trace elements, and magnetic susceptibility are the commonly used proxies.

The continental shelf and continental margin preserve sediments and paleoclimate records and therefore form an important area to study the source, processes, and depositional environments. The Bay of Bengal, in the northeastern Indian Ocean a large and relatively shallow embayment, lies roughly between 5° and 22°N and 80° to 90°E and occupies an area of about 2,173,000 sq km (839,000 square miles) is one of the known locations for paleoclimate study. The Bay of Bengal seafloor morphology is presented in Fig. 8.1. The Bay annually receives a large amount of freshwater and sediment (2000 m tons) during the NE and the SW monsoons from the Himalayan and the Indian peninsular rivers, respectively. The arid dry conditions prevail in the Himalayan regions and nearly, temperate humid conditions prevail across the Indian subcontinent. The area is sensitive to changes in temperature and monsoon intensity due to this difference. These changes are recorded in the sediments of the Bay of

Bengal over the years. Further, the large sediment influx to the bay makes it an ideal location for deciphering the signature of the paleoclimate in the high sedimentation area.

Several researchers have studied different proxies in the sediments of the east coast of India and the western Bay of Bengal (Kolla and Rao, 1990; Chauhan et al., 2005; Pattan et al., 2008; Panchang and Nigam, 2012; Bejugam and Nayak, 2019a). Different paleoclimatic proxies such as detrital and organic material, clay minerals, carbonates, metals, pollens have been studied in the Bay of Bengal sediments (Wei et al., 2003). Based on the study carried out on suspended sediment transport and dynamics Barua et al. (1994) revealed that sediment transport is a function of tidal energy within the Ganges–Brahmaputra river system. Chauhan et al. (2005) reported different dispersal patterns for the terrigenous flux of the Ganges–Brahmaputra rivers during SW and NE monsoons. Goldberg and Griffin (1970) reported that river-borne solids control the clay mineral distributions in the Bay of Bengal and Rao et al. (1988) stated that clay minerals represent their sources but their preservation is controlled by the energy conditions. Kolla and Rao (1990) have related the presence of high smectite, sillimanite, garnet in the sediments to supply from peninsular Indian rivers and the presence of high illite, hornblende, epidote to supply from the Himalayan rivers. Raman et al. (1995) have stated that the clay mineral of the distal Bengal Fan is controlled by the relative rates of sediment supply from the Himalayan and Deccan sources. Reddy and Rao (2001) reported an increase in montmorillonite proportion during Holocene as the Ganges derived sediments are diluted by supply from the peninsular rivers. Chakrapani and Subramanian (1990) using the geochemical proxies of the Mahanadi basin observed that reworking caused the finer sediments to be deposited downstream. Raj and Jayaprakash (2008) revealed an association of higher content of trace metals with higher finer grain size and organic carbon. Pattan et al. (2008) based on geochemistry of surface sediments confirmed the minor contribution of Ganges–Brahmaputra rivers to the Krishna–Godavari basin compared to peninsular rivers.

Crowley et al. (1998) observed that contribution of Himalayan and Indian subcontinent sources to distal fan sedimentation varied with time and uplift, weathering and erosion rates, eustatic sea-level changes and switching of fan channels controls sediment supply. Kuehl et al. (1989) employing sedimentological and geochronological proxies reported that the highest sediment accumulation from the Ganges–Brahmaputra river takes place near the head of the Swatch of No Ground and suggested that the Swatch of No Ground is a major conduit for the seaward transport of sediments from the Bengal shelf. The variations in paleoclimate and monsoon variability in the Bay of Bengal from the Last Glacial Maximum (LGM) to the late Holocene period was explained by Govil and Naidu (2011), Rashid et al. (2011), Ponton et al. (2012), and Phillips et al. (2014). Govil and Naidu (2011) reconstructed SSS and SST of Bay of Bengal to understand the rainfall variability associated with SW monsoon over the past 32 ka. Their results showed that during LGM the western Bay of Bengal was ~3°C cooler than today. Rashid et al. (2011) studied the Late Glacial to Holocene ISM variability based on sediment records from the Bay of Bengal and using SST and $\delta^{18}O$ suggested that seawater was colder during the LGM compared to the early Holocene. Ponton et al. (2012) reconstructed the Holocene paleoclimate during Core Monsoon Zone off Godavari river and reported that Core Monsoon Zone aridification intensified in the late Holocene through a series of sub-Millenial dry episodes. Phillips et al. (2014) used multiproxy records to reconstruct monsoon induced variations in productivity and lithogenic sediment flux since past 110 ka from a northern Bay of Bengal core. Many researchers using various proxies of sediment cores have carried out the study in the Bay of Bengal to reconstruct the paleomonsoon intensity (Krishnamurthy and Goswami, 2000; Pothuri et al., 2014), paleocirculation (Gourlan et al., 2010), paleoproductivity (Prajih et al., 2018; Bejugam and Nayak, 2019a), and changing weathering conditions (Symphonia and Nathan, 2018; Bejugam and Nayak, 2019b; Kangane et al., 2019). Attempts also have been made to understand the monsoon precipitation by using oxygen isotope values of waters in the Bay of Bengal since the last glaciations (Ahmad et al., 2008; Rashid et al., 2011; Raza et al., 2014).

8.1.1 Scope of the study

Understanding the response of proxies off major rivers delivering huge amounts of freshwater and sediment to the ocean is important and is the scope of this article. This chapter describes the results of the analysis of sediment multicores and gravity core sampled and analyzed for sediment components namely sand, silt clay; clay minerals, and metals from the western continental shelf region in the Bay of Bengal to understand the source, processes, depositional environments and changing climatic conditions including monsoons.

8.2 Methodology

8.2.1 Sampling area

The western continental shelf and slope sediments of the Bay of Bengal off Hooghly, Mahanadi, Vamsadhara, Godavari, Krishna, and Pennar river mouth regions constitute the present study area. The continental shelf region here is with variable width, flat and broad near-shore, and steeper in deeper water depths. The western Bay of Bengal is prone to cyclonic storms in the postmonsoon season during prevalent NE monsoon winds resulting in high rainfall in coastal regions (Lin et al., 2009). However, the bulk of the precipitation is received during the SW monsoon (June–September) intensifying sediment influx into the coastal Bay of Bengal (Nair and Ittekkot, 1991). The surface hydrographic circulation in the Bay of Bengal gets complicated due to the seasonal reversal in wind directions and high freshwater influx (Varkey et al., 1996). The high freshwater influx reduces the salinity of the water off the river mouths (Suokhrie et al., 2018) and forms the stratified freshwater and saline water layers making a barrier for vertical mixing.

The Hoogly river along its course consists of Archean gneisses, sandstones, feldspathic quartzites, metamorphosed Archean–Proterozoic sediments, and recent alluvium drained from Ganges (Singh et al., 2007). The Mahanadi river emerges from the Eastern Ghats and the bulk of the geology along its course is composed of felsic rocks of khondalites, charnockites, granites, gneisses and the limestones, sandstones, and shales of the Gondwanas (Chakrapani and Subramanian, 1990). Krishna and Godavari rivers flow across the Indian peninsular shield constituting Precambrian, Deccan basalts, and Dharwar formations. The detailed geology of the river basins is presented in Fig. 8.2. The Peninsular rivers drain enormous sediment load onto the western continental shelf of the Bay of Bengal under the influence of NE and SW monsoons. The sediment flux data from 1986 to 2006 (CWC—Central Water Commission) for Mahanadi river is $30.6*10^6$ tons/yr, Godavari river $170*10^6$ tons/yr, Krishna river $9*10^6$ tons/yr, and Pennar river $3*10^6$ tons/yr (Panda et al., 2011) while for Hooghly river a tributary of the Ganges it is about $65*10^6$ tons/yr (Mukhopadhyay et al., 2006).

The high sediment accumulation rate during the late Holocene in the Bay of Bengal was reported. The rates measured using the ^{210}Pb method, Off Hooghly, was ~2.0 cm/year (Kuehl et al., 1989; Suckow et al., 2001). Off Godavari it was 0.25 cm/yr for cores between 30 and 100 m water depths (Kalesha et al., 1980; Kiran et al., 2015). In deeper water depths of 600–1400 m, rates measured by the

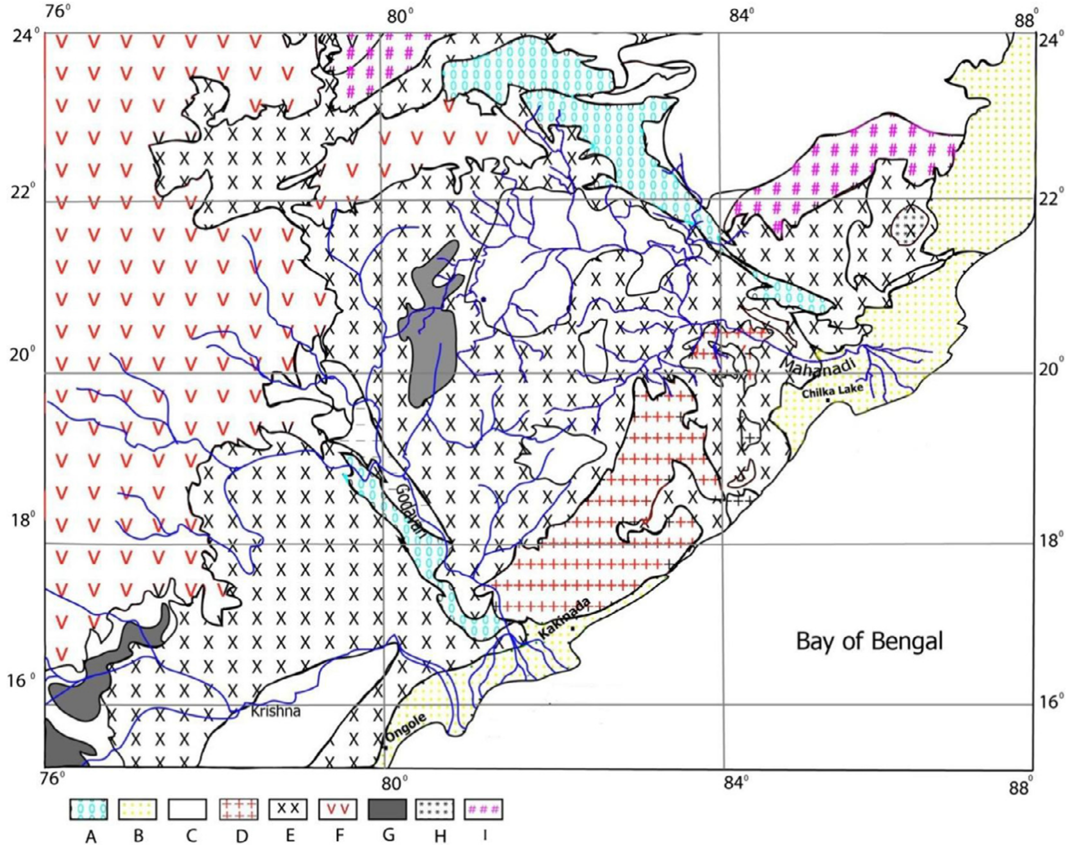

FIGURE 8.2

Geological map of Mahanadi, Godavari, and Krishna drainage basins. A, Gondwana sediments; B, Quaternary sediments; C, Mid–Late Proterozoic sediments; D, Archean charnockite and khondalite; E, Archean–Proterozoic gneissic complex; F, Deccan basalt; G, Early Proterozoic ELSST073-08-granites; H, Archean–Proterozoic Singhbhum metamorphic complex (after Mazumdar et al., 2015).

^{14}C method (Mazumdar et al., 2012, 2014; Usapkar et al., 2016) were 0.24 cm/yr off Mahanadi river and 0.34 cm/yr off Krishna river. In these studies, the dating was carried out on the foraminiferal species *Globigerina ruber* and *Globigerina sacculifer*.

8.2.2 Sampling methods

The sediment cores used for the present study were collected onboard RV Sindhu Sankalp (Cruise No. 35) in June 2012 off Hooghly using spade corer and onboard RV Sagar Kanya (Cruise No. 308) in January 2014 using multicorer off Mahanadi, Vamsadhara, Godavari, Krishna, and Pennar rivers and gravity corer off Mahanadi river. The cores off Hooghly river were collected from the western side of

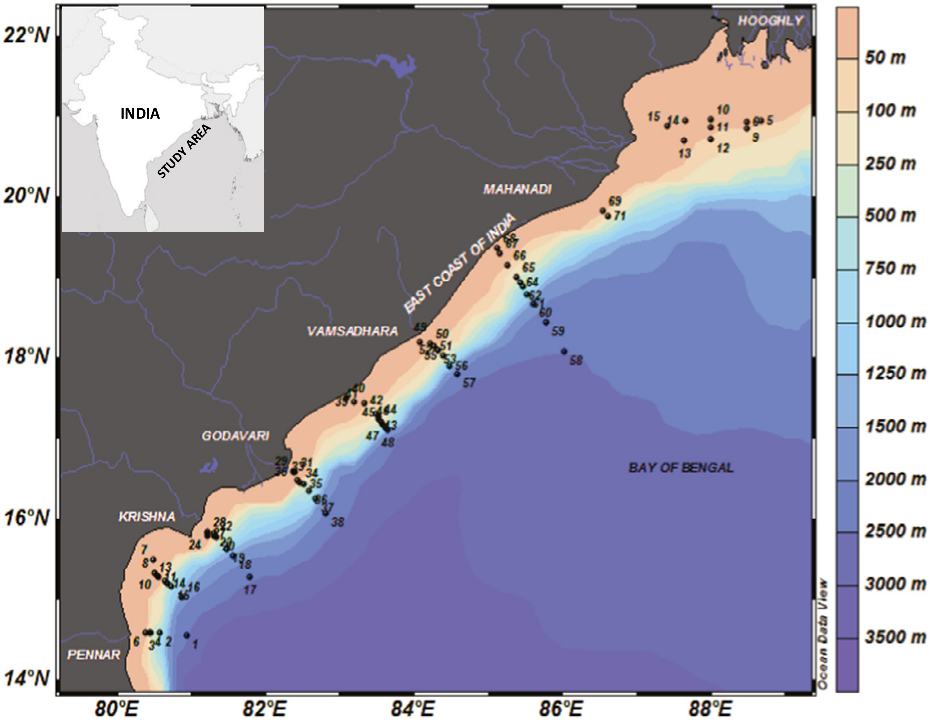

FIGURE 8.3

Sampling locations of sediment cores collected from western Bay of Bengal off Hooghly, Mahanadi, Godavari, Vamsadhara, Krishna, and Pennar River mouth regions (Bejugam, 2018).

the “Swatch of no ground” submarine canyon. From the several cores collected from 25 to 2500 m water depths, 70 surface samples, 25 short cores (Fig. 8.3), and one gravity core collected at $19^{\circ}82^{1}$ N and $86^{\circ}56^{1}$ E at 101.9 m water depth were utilized for the present study. The samples were collected along nearly latitudinal transects off major rivers and the water depth at the sampling location was recorded with the help of an echo-sounder. The multicores (Fig. 8.4) and gravity core were subsampled at 1cm interval onboard, preserved in cold storage and alternate samples were used for analysis.

8.2.3 Laboratory analysis

In the laboratory, the sediment sample was oven-dried and a part of the sample was used for grain size and clay mineral analysis. Another part of the sediment was ground into a fine powder using an agate mortar and pestle and used for the analysis of inorganic elements. For sediment grain size (sand: silt: clay) analysis, samples were processed to remove salinity and then treated with 10 ml of 10% sodium hexametaphosphate to dissociate clay particles and then to oxidize the organic matter using 5 ml hydrogen peroxide. The pipette method based on Stoke’s settling velocity principle (Folk, 1968) was

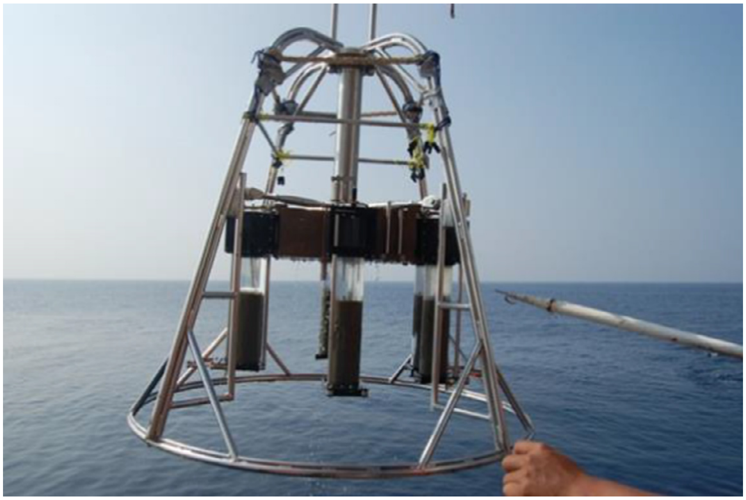

FIGURE 8.4

Retrieving multicorer with sample onboard.

employed to determine the grain size of sediment samples. For the clay mineral analysis, the procedure given by Rao and Rao (1995) was adopted. On prenumbered slides, 1 ml of clay was evenly spread and these slides were gylcolated using ethyl glycol vapors for 1 hour at 100°C. The slides were later scanned on Rigaku Altima IV X-Ray diffractometer using nickel-filtered CuKα radiation from 3° to 30° $\Delta 2\Theta$ at 1.2° $\Delta 2\Theta$/min. To identify and quantify the clay minerals the procedure given by Biscaye (1965) was used.

Employing the procedure given by Jarvis and Jarvis (1985) ground sediment samples were digested to total decomposition for metal analysis. The acid mixture HF, HNO_3, and $HClO_4$ in a ratio of 7:3:1 was used to digest the sediment sample in a Teflon vessel. Along with the samples, a certified reference standard JLK-1 from the Geological Survey of Japan was also digested to test the analytical accuracy of the method for gravity core samples. Later the samples and standards were analyzed on atomic absorption spectrophotometer (Thermo Scientific- SOLAAR M6 AAS model). The average recovery for Mn was 95.3%, for Fe 96.2%, and for both Zn and Pb, it was 97.1%. For the multicore and spade core samples, the concentrations of major and trace elements (Al, Fe, Ti, Mn, Zn, Pb) were determined using Varian AA 240 FS flame atomic absorption spectrometry with an air/acetylene for Fe, Mn, Zn, and Pb; and for Al and Ti nitrous oxide/acetylene was employed at specific wavelengths. To test the analytical accuracy of the method, together with the samples, certified reference standard MAG-1 was analyzed for the same metals. The average recoveries for Al, Fe, Ti, Mn, Zn, and Pb were 88%, 94%, 95%, 95%, 96%, and 96%, respectively. The Merck chemical standards were used to calibrate the instruments and at regular intervals, the recalibration checks were performed.

Gravity core was processed for obtaining age dates. Mixed planktic foraminifera was picked at >63 μm size fraction from few sediment subsamples for measurement of AMS ^{14}C age. The dating procedure was carried out at the Centre for Applied Isotopic Studies, University of Georgia, USA.

Table 8.1 Range of sand, silt, and clay in surface sediments along transects from Hoogly to Pennar rivers.

Transect	Off river mouth	Sand (%)	Silt (%)	Clay (%)
1	Hooghly river mouth—North	3.97–94.43	1.39–56.59	3.20–42.08
2	Hooghly river mouth—South	1.43–48.94	22.58–59.67	28.48–62.64
3	Mahanadi river mouth—North	Highest at 102 m water depth	Highest at 102 m water depth	Highest at 507 m water depth
4	Mahanadi river mouth—South	0.30–42.43	6.00–25.74	44.64–64.20
5	Vamsadhara river mouth	0.46–61.14	10.34–32.93	27.76–89.20
6	Between Godavari and Vamsadhara river mouths	0.33–78.07	7.58–26.80	10.72–90.56
7	Godavari river mouth	0.27–2.70	29.05–59.57	40.16–83.30
8	Krishna river mouth	0.22–9.01	14.82–57.39	33.60–84.72
9	Between Krishna and Pennar river	0.41–4.54	18.68–24.90	34.88–80.08
10	Pennar river mouth	0.17–3.83	11.77–28.50	68.52–87.50

Calibration of ^{14}C ages was carried out using the Marine13 dataset (Reimer et al., 2013) drawn from Calib 7.1 (Stuiver et al., 2017) online calibration program; under the assumption that the top of the sediment core was undisturbed, it was assigned the year of core collection (2014). Further, considering the constant rate of sedimentation between the obtained dates, the ages of the remaining samples were calculated.

8.2.4 Data processing

The software's Grapher-8.0, Adobe Illustrator, and ODV-4.0 (Ocean Data View) were used for preparing the illustrations.

8.3 Results and discussion

8.3.1 Surface and spade/multicore sediments—source and processes

8.3.1.1 Sediment components

The range of sand, silt, and clay for each transect is provided in Table 8.1 and the data were plotted on Ocean Data View with the color bar on the right depicting the concentration (Fig. 8.5). The sediment components showed a decrease in grain size from north to south, that is, from off Mahanadi, through off Godavari and off Krishna to off Pennar river mouths. Sand content exhibited a decrease from off Hooghly river mouth to off Pennar river mouth in the continental shelf samples up to a depth of 200 m. Sand content (Fig. 8.5) was highest (94.43%) in transect 1 off Hooghly river mouth at 42 m water depth and least (0.63%) off Godavari river mouth at a water depth of 107 m. In the deeper regions in the slope and abyssal plains between water depths of 200 and 2500 m the sand content was low and

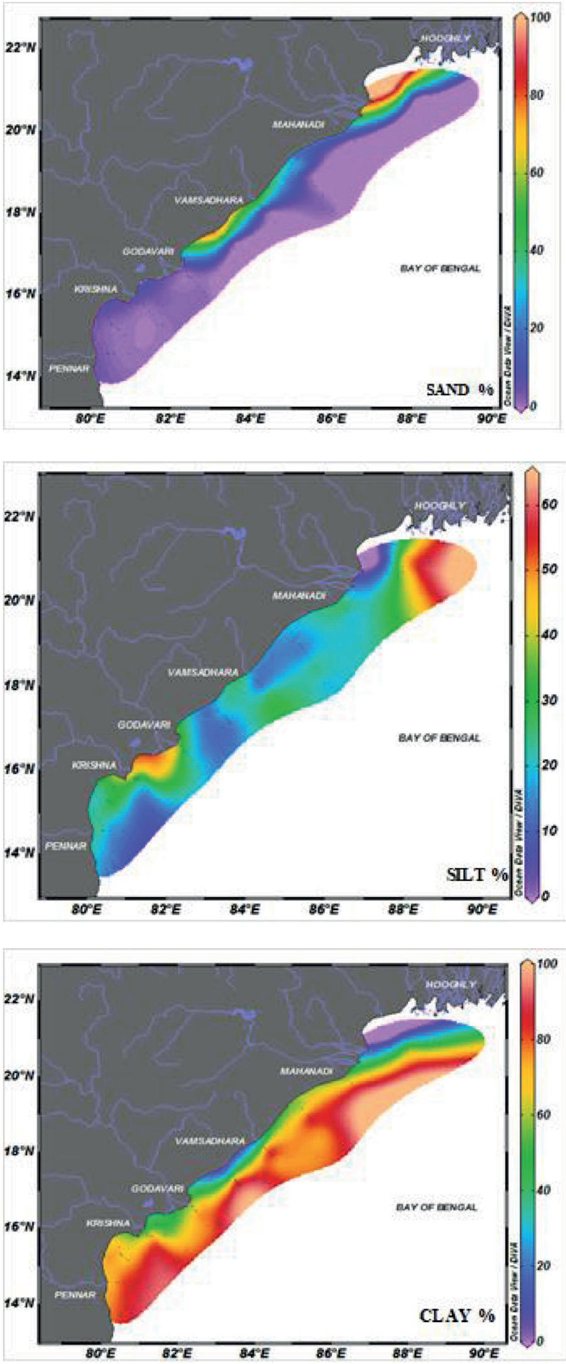

FIGURE 8.5

Distribution of sand, silt, and clay contents in the surface sediments of the study area.

varied in a small range of 0.17% and 2.98% except at 280 m water depth where the sand was slightly higher at 7.36%. Silt content (Fig. 8.5) also displayed a decreasing trend from north to south with an exception at few stations at shallower water depths up to a depth of 500 m especially off Godavari and off Krishna river mouth regions where its concentration was higher. Silt content was highest (59.67%) in transect 2 off Hooghly river mouth. Clay content (Fig. 8.5) increased from north to south with the lowest clay content (3.20%) off Hooghly river mouth and highest clay concentration (93.70%) at 1073 m water depth off Mahanadi river mouth. In the deeper water depths, clay content was consistently high varying between 65.04% and 93.70% in the majority of the samples. Along all transects from north to south at shallower water depths closer to the coast the clay content was low.

Further, when the average of down core values of sediment components are compared based on the water depths along the transects in the range of 31–83 m, 104–107 m, 202–260 m, 495–499 m, and 645–1005 m sand content exhibited an overall decrease from shallow to deeper water depths in the study area (Bejugam, 2018). The silt content showed an overall large range of variation in shallow regions compared to deeper regions and the clay distribution showed higher values toward deeper water depths compared to shallow depths in the study area.

The sediments released from a river basin provide useful information on their source and transportation history, and hydrodynamic conditions prevailed during the time of sediment deposition. Topography and climate in the source area are the main factors controlling the processes like weathering, erosion, and transportation, which determine the dispersal system connecting source and basin (Jackson and Nordstorm, 2011; Weltje and von Eynatten, 2004).

The grain size of sediment reveals the sediment transportation pathways, energy conditions, and the intensity of monsoon precipitation (Prizomwala et al., 2014; Basavaiah et al., 2015). Also, the grain size is related to the bathymetry of the depositing site, sediment input, and processes (Lopez, 2017). Sediment size analysis of surface and spade/multicore sediments along the western Bay of Bengal revealed that overall, sand content was low while silt and clay was the dominant sediment fraction. However, it was noted that along all transects the sand content was relatively high up to a water depth of 100 m and clay was dominant in sediments deeper than 1000 m in the continental slope region. The high silt content was noted in samples near the river mouth except off Hooghly river mouth. The sediment size, in general, decreased away from the coast and with increasing water depth in the study area. The occurrence of high sand content in the shallow sediments signifies higher hydrodynamic energy, strong wind activity, and closer source area (Babeesh et al., 2017). Furthermore, a loss of energy offshore may be unable to carry the sand toward deeper water depths explaining higher clay deposition in deeper regions. Finer sediments from the rivers may have been transported directly toward the continental slope and abyssal plain regions and deposited there. Further, grain size decreased from off Hooghly river mouth, through off Mahanadi, off Vamsadhara, off Godavari, and off Krishna to off Pennar river mouth regions indicating a north to south transport of sediments and relatively high energy environment prevailing off Hooghly and off Mahanadi river mouths which enabled the deposition of coarser material and prevented the accumulation of finer sediments. A probable loss of energy southward inhibited the transport of coarse grain sediments toward the south and facilitated the deposition of finer sediments. Kumar et al. (2010) suggested that the dominance of finer clay particles indicated low energy conditions and facilitated the deposition of finer sediments. In transects off Hooghly river mouth, overall sediment size decreased from west to east, that is, toward the "Swatch of No Ground"—submarine canyon, indicating that probable current direction was toward the east which transported the sediment. Fine-grained sediments were possibly carried by the currents formed at high energy conditions near the river mouth toward east parallel to the coast and also toward the south and southeast direction. Later these fine-grained sediments upon redistribution may have been deposited in the eastern and southeastern parts of this area. The distribution of sediment components in southern transects off peninsular rivers indicated a possible direction of transport from coastal to deeper water regions indicating sediment supply from these rivers to the bay.

The single most important climate factor in the south-east Asian regions is the monsoon and therefore, paleoclimatology in the Indian context is largely the reconstruction of the monsoon through time. During the LGM, the snow cover over the Tibetan plateau and central Asia decreased the land–ocean temperature contrast during summer and increased during winter leading to weaker SW monsoon and strengthened NE monsoon (Tiwari et al., 2009). Monsoon records from the Arabian Sea displayed similar patterns to the adjacent Asian and African regions (Duplessy, 1982; Sirocko et al., 1991; Overpeck et al., 1996) inferred from strong winter monsoon during LGM as observed by enhanced NE monsoon current during that period. This was probably because the Indian and Chinese monsoons have similar sub-Milankovitch periodicities (Sarkar et al., 2000). Unlike the Arabian Sea and the South China Sea, paleomonsoon interpretations from Bay of Bengal sediment cores are limited except few recent reports (Rashid et al., 2011; Govil and Naidu, 2011; Ponton et al., 2012; Tripathy et al., 2014). Further, the majority of the paleomonsoon records are based chiefly on foraminiferal species (*Globigerina ruber, Globigerina bulloides*), magnetic susceptibility studies, sea surface temperature and salinity but very seldom based upon lithogenous proxies such as grain size, clay minerals, and inorganic elements. These proxies are typical to terrestrial sources and are directly linked to weathering and the intensity of monsoon precipitation. The down-core sediment component variation in cores off Hooghly river mouth indicate that a change in the trend of the grain size distribution toward coarser size above 10 cm (Bejugam and Nayak, 2016a) indicating a probable change in hydrodynamic conditions due to floods, a storm, an increase in tidal current or a change in hydrodynamic conditions which might have taken place with a possible direction of the storm toward the east. In one of the earlier studies, McLaren and Bowles (1985) created a sediment transfer model and inferred that sediments tend to become finer in the direction of transport with a decreasing energy regime. A higher concentration of sand in the upper section of cores off Mahanadi and off Pennar river mouths is evidence of abundant terrestrial input in recent years probably due to higher rainfall. Also, higher sand from the bottom up to a depth of 10 cm and in some cores from the bottom up to a depth of 20 cm may be due to a flood event during higher rainfall which brought with it abundant terrestrial material. Basu (1976) emphasized that grain size is an indicator of climate change where an increase in sand fraction suggested intensification of the SW summer monsoon. The relative changes in concentration of grain size are a direct representation of monsoonal variation where an increase in coarser fraction indicates that the hinterland region received good monsoonal precipitation leading to enhanced weathering (Basavaiah et al., 2015). The velocity of the transporting medium increases during high rainfall periods resulting in enhanced entry of coarse sediments. Conversely, due to the reduction in stream velocity during low rainfall periods finer sediment influx is enhanced (Conroy et al., 2008).

8.3.1.2 *Clay minerals*

Off Hooghly and off Mahanadi river mouths, in all the surface samples illite was the predominant mineral followed by other clay minerals namely kaolinite, smectite and chlorite while off Godavari and off Krishna river mouths, smectite was the dominant clay mineral which was followed by kaolinite, illite, and chlorite. Off Pennar river mouth smectite was the dominant clay mineral followed by illite,

Table 8.2 Range of illite, smectite, kaolinite, and chlorite in surface sediments along transects from Hoogly to Pennar rivers.

Transect	Off river mouth	Illite (%)	Smectite (%)	Kaolinite (%)	Chlorite (%)
1	Hooghly river mouth—North	78.50–81.86	3.26–7.69	9.85–12.59	2.29–5.61
2	Hooghly river mouth—South	75.14–79.01	4.50–11.60	9.47–13.51	1.76–4.50
3	Mahanadi river mouth—North	Highest (63.03) noted at 507 m water depth			
4	Mahanadi river mouth—South	43.77–65.84	10.29–22.26	17.61–30.87	3.09–6.53
5	Vamsadhara river mouth	43.84–66.67	10.61–26.67	18.18–34.09	3.43–4.64
6	Between Godavari and Vamsadhara river mouths	30.77–72.34	5.32–40.57	17.55–35.16	3.12–6.50
7	Godavari river mouth	9.52–53.33	25.33–69.84	13.53–39.51	2.29–8.57
8	Krishna river mouth	7.41–28.92	37.35–79.84	9.61–26.24	0.87–7.50
9	Between Krishna and Pennar river	3.33–15.72	67.03–82.53	7.21–16.72	1.96–3.52
10	Pennar river mouth	14.48–28.76	51.63–70.14	11.61–18.04	2.25–5.60

kaolinite, and chlorite (Table 8.2). The variation in concentration of clay minerals when observed from north to south (Fig. 8.6) it was noted that smectite content was very low off Hooghly river mouth in the north and increased slightly off Mahanadi and off Vamsadhara river mouths, while off Godavari, off Krishna, and off Pennar river mouths, smectite increased significantly except for sample MC-06 off Pennar river mouth where smectite content was relatively low (Fig. 8.6). The lowest smectite content (3.26%) was noted at 31 m water depth off Hooghly river mouth while the highest smectite (82.53%) was observed at 76 m water depth south off Krishna river mouth. Illite concentration (Fig. 8.6) was high off Hooghly river mouth in the north and decreased southward but was the dominant clay mineral off Mahanadi and off Vamsadhara river mouths and further decreased significantly off Godavari, off Krishna and off Pennar river mouths except for sample MC-06 off Pennar river mouth where illite content was high. The highest illite content (81.86%) was observed at 31m water depth off Hooghly river mouth while the least illite content (3.33%) was observed at 275 m water depth south off Krishna river mouth. Kaolinite concentration (Fig. 8.6) was low off the Hooghly river mouth in the north and increased southward. It was also observed that in the shallow water regions off the river mouths kaolinite was enriched specifically off Godavari river mouth. Kaolinite content was highest (39.51%) at 107 m water depth off Godavari river mouth, while the least kaolinite content was observed at 500 m water depth off Krishna river mouth (south transect). Chlorite content was consistently low (Fig. 8.6) throughout the study area from north to south varying within a small range. However, off Hooghly, off Mahanadi, off Vamsadhara and up to off Godavari river mouth chlorite was slightly higher and decreased significantly off Krishna river mouth. The highest chlorite content (8.57%) was noted in sample MC-34 off Godavari

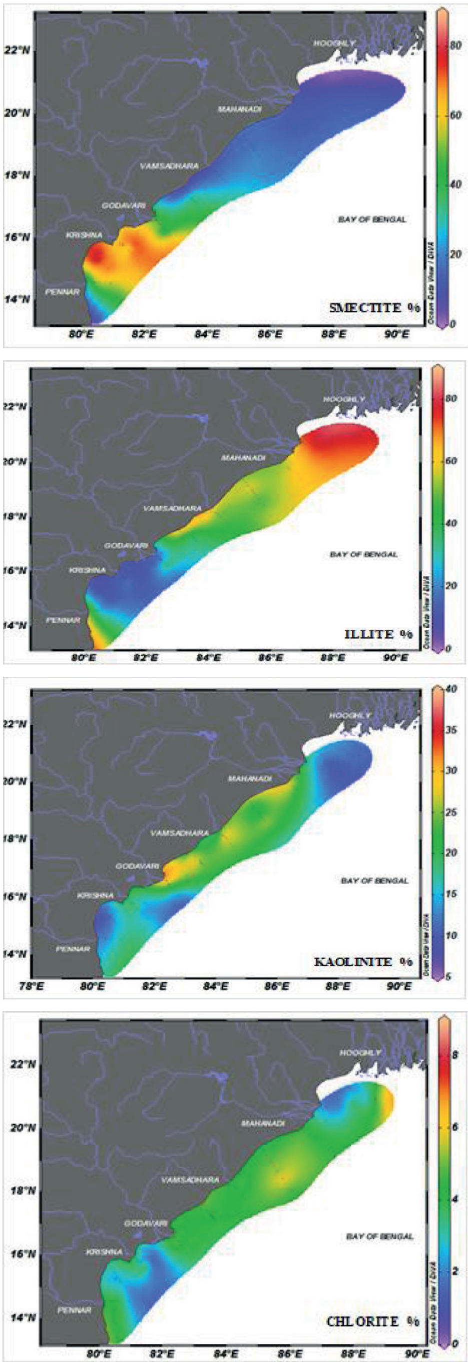

FIGURE 8.6

Distribution of clay minerals in the surface sediments of the study area.

river mouth at 744 m water depth while the least chlorite content (0.87%) was observed off Krishna river mouth at a deeper water depth of 2006 m.

When the average concentration of clay minerals was compared from north to south for a range of water depths 31–83 m, 104–107 m, 202–260 m, 495–499 m, 645–767 m, and 979–1005 m, the smectite content increased and illite content decreased from off Hooghly, through off Mahanadi, off Vamsadhara, off Godavari, off Krishna to off Pennar river mouths (Bejugam, 2018). Kaolinite content increased and chlorite decreased from off Hooghly river mouth in the north to off Pennar river mouth in the south at different depth ranges with few exceptions.

While illite was the predominant clay mineral in cores off Hooghly, off Mahanadi, and off Vamsadhara river mouths, abundant smectite characterized sediments off Godavari, off Krishna, and off Pennar river mouths. The distributions of the clay minerals in sediments off Hooghly river mouth represent large input from Himalayan sediments. Clay minerals are mainly formed by hydrolytic disintegration of primary aluminosilicates (Singer, 1984) and undergo weathering under particular climatic conditions and therefore have been successfully used as paleoclimate indicators (Wahsner et al., 1999; He et al., 2013). The Hooghly river is a tributary of the Ganges which originates in the Himalayas and drains under cold climatic conditions. On its course of transport, it erodes Precambrian formations in its upper channels and Rajmahal Traps and recent alluvium in its lower channels (Rao et al., 1988). Illite, a predominant mineral off Hoogly river, is a residual product of mechanical weathering under arid conditions with its source from the Himalayan region indicating the role of NE monsoon as a major factor in the transportation of sediments. Higher illite percentage in the sediments from transect 1 off Hooghly river mouth associated with more sand strongly supports the release of sediments from Himalaya during NE monsoon or through glacial melt due to the effect of climate change. Illite is an alteration product of muscovite which is associated with phyllites, schists, and shales; and muscovite mica which is a dominant mineral in the Himalayas must be the major source for illite.

Off Mahanadi river mouth as compared to off Krishna–Godavari river mouths high illite content obtained indicates its supply from felsic source rocks, from Archean–Proterozoic gneissic complex (Mazumdar et al., 2015) as K-feldspars are easily weathered to clay minerals (Chen et al., 2010). The concentration of Ganges transported illite decreased southward indicating its dilution by the input from peninsular rivers. Further, lower concentrations off Godavari, off Krishna, and off Pennar river mouth regions may be due to a loss of energy southward which restricts illite-rich sediments to reach toward the south. However, appreciable illite was also noted in few sections down the core off Krishna and off Godavari as the Krishna–Godavari river's flow over the charnockites and granites of Archean age. These rocks weather under warm and humid conditions can produce mixed clays (Vuba et al., 2013). Higher illite concentration was also noted in a surface sample off Pennar river mouth, however, possible conversion of smectite to illite could be ruled out as diagenetic conversion takes place at high temperatures under greater depths (Grim, 1968; Mazumdar et al., 2015).

Regional climatic conditions and variations in latitudes have a high influence on sources of marine clays (Naidu et al., 1995; Petschick et al., 1996). Smectite content increased abundantly in cores off Godavari, off Krishna, and off Pennar river mouths and supports the statement that it is considered as a low latitude clay mineral (Biscaye, 1965). High smectite off these southern rivers of the study area may be due to the release by chemical weathering of basic volcanic igneous rocks namely Deccan basalts (Raman et al., 1995; Kulkarni et al., 2015) under the prevalent humid tropical climatic conditions. Also, smectite must have been added from black cotton soils and crystalline Archean rocks. Kolla and Rao (1990), Somayajulu et al. (1993), and Pattan et al. (2008) also reported earlier high smectite in sediments off Godavari–Krishna river mouths. Minor smectite concentration observed in few sections in cores off Mahanadi river mouth may have been contributed from the weathering of eastern Deccan traps over which a tributary of Mahanadi passes through (Rickers et al., 2001). An appreciable concentration of kaolinite observed in few sections in cores off Mahanadi and off Vamsadhara river mouths may have been formed from alteration of aluminosilicate minerals like feldspar leaching from Archean granites, gneisses, charnockites, and khondalites which are the dominant rock types in the region.

Further, illite increased and kaolinite decreased at deeper than 1500 m water depth. High kaolinite concentration in shallow waters may be attributed to its higher settling velocity (Whitehouse et al., 1960; Prithviraj and Prakash, 1990). Less contribution of kaolinite from Ganges–Brahmaputra rivers was earlier attributed to possible equatorward dispersal (Chauhan and Vogeslang, 2006). Higher kaolinite content in cores located at shallower regions off Godavari river mouth may be contributed from the "Red beds" which is a major rock type near the Vishakapatnam coast as also reported by Malathi (2013) earlier. Among the clay minerals, chlorite concentration was lowest in the sediments and the values obtained were in range with the chlorite percentage reported earlier by Raman et al. (1995) and Philips et al. (2014). Chlorite content was low from cores in the region due to prevailing humid tropical conditions which makes it unstable (Thamban et al., 2002). It has therefore been observed from the clay distribution that the source of clays in sediments is largely from the weathering of rocks from the terrestrial region.

In cores off Godavari and off Pennar river mouths with increasing water depth average smectite increased which probably is due to its finer size that made smectite remain in suspension for a longer time and further even weak currents could transport it to deeper region. Salinity is low in waters near the river mouth. Illite is more stable than smectite under less saline conditions explaining the slightly higher illite content near the river mouth. Such inverse relation among clay minerals is observed in many studies worldwide due to their different settling rates (Aksu et al., 1998). Also, the flocculation of individual minerals varies for saline conditions (Rao et al., 1988; Patchineelam and De Figueiredo, 2000). Moore and Reynolds (1989) and Liu et al. (2010) reported that clay mineral distribution also depends on energy conditions. It is known that illite and kaolinite due to their coarser size, deposit under high energy conditions and smectite with relatively finer size gets deposited under low energy conditions. A higher concentration of smectite off Godavari, off Krishna, and off Pennar river mouths suggests that low energy prevailed in this region. Abundant illite off Hooghly and off Mahanadi river mouths indicates high energy conditions prevalent during the time of deposition. This hydrodynamic variation from north to south was observed in grain size variation as well.

Clay minerals in marine sediments provide information on overall climate impact (Singer, 1984). In cores off Hooghly river mouth, illite is the dominant clay mineral transported to the region probably during the NE monsoon period. However, an appreciable concentration of smectite was noted at 5 cm in all cores off Hooghly river mouth in the north which must have been brought in during intense SW monsoon winds blowing toward the region. In cores off Mahanadi and Vamsadhara river mouths as well illite was the dominant clay mineral. However, high smectite was noted in a few sections in these cores suggesting increased smectite discharge from the terrestrial region during increased SW monsoons. At 15 cm section in majority of the cores off Godavari river mouth, at 20 cm in cores off Krishna river mouth and; 25 and 5 cm in cores off Pennar river mouth smectite decreased and illite increased in concentration indicating the prevalence of NE monsoon during that period.

8.3.1.3 Metals

The bulk metals in marine sediment are useful indicators of terrigenous provenance and dispersal patterns (Kolla and Rao, 1990; Yuste et al., 2014), as well as paleoclimatic conditions in the source areas (Thiry, 2000; Thamban et al., 2002; Dou et al., 2010). Al, Ti, and Fe are the major lithogeneous contributors to the marine sediment and can be used to trace the geology, weathering history of source rocks, and diagenesis. The bulk metal concentration is also useful in understanding postdepositional processes. Further, the geochemistry of the individual elements (Rollinson, 2014) and their abundance varies conspicuously with the intensity of monsoonal precipitation (Pattan et al., 2012). The metal content in the surface sediments was analyzed for samples off Mahanadi river mouth to off Pennar river mouth (Table 8.3). In transect 3 element concentrations varied in a small range between stations.

From north to south Al content (Fig. 8.7) was largely consistent except at the shallow region off Vamsadhara river mouth where Al content was low. Al content ranged between 4.43% off Vamsadhara river mouth at 50 m water depth and 10.75% at 520 m water depth along transect 6. Fe concentration (Fig. 8.7) increased from north to south and varied between 2.95% at 55 m water depth in the transect south off Vamsadhara and 9.70% at 40 m water depth off Godavari river mouth. Ti was high in sediments off Godavari and off Krishna river mouths while off Mahanadi and off Vamsadhara river mouth in the north and off Pennar river mouth in the south Ti was low in the sediments (Fig. 8.7). Ti ranged from 0.28% off Mahanadi river mouth at 105 m water depth and 1.90% at 32 m water depth off Krishna river mouth. Mn varied in a small range from north to south (Fig. 8.7). In the intermediate water depths, Mn was however low as compared to deeper water depths. Mn ranged between 0.03% at 507 m water depth off Mahanadi river mouth and 1.20% at 2488 m water depth off Vamsadhara river mouth. Zn was largely constant from north to south (Fig. 8.7) except off Pennar river mouth and also at shallow water depths where Zn was slightly low. Pb decreased from north to south wherein off Mahanadi and off Vamsadhara river mouth transects Pb was high and decreased in the south off Godavari and off Krishna river mouth transects (Fig. 8.7).

The core average of Fe, Ti, and Mn concentration decreased from shallow to deeper water depths in all the transects except in core MC-66 off Mahanadi river mouth and also in shallow cores off Vamsadhara river mouth where average metal content was slightly low. Fe, Ti, and Mn content increased toward south from off Mahanadi to off Godavari and off Krishna river mouths in the shallow as well as deep-water sediment cores (Bejugam, 2018).

Elemental chemistry plays a significant role in the assessment of the sedimentary environment and provenance (Yiyang and Mingcai, 1994). Al is a major constituent of sediments attained from continents (Taylor and McLennan, 1985) and is commonly used to measure the extent of accumulation of the lithogenous component (Murray and Leinin, 1996). The average concentrations of Al in different rock types differ by about 10% from the average crustal value (Turekian and Wedepohl, 1961; Taylor and McLennan, 1985) and hence useful as a lithogenous source indicator. The Al concentration in the majority of the surface and core samples ranged from 7% to 9% indicating its uniform terrestrial source. This suggested that changes in Al accumulation along transects were limited. It is close to the crustal PAAS value of 9.94%. Fe concentration in sediments was higher off Godavari, off Krishna and off Pennar river mouths as compared to off Mahanadi and off Vamsadhara river mouths and also higher than crustal PAAS value of 5%. Taylor (1964) recorded an average of 5.63% Fe in continental crust sediments and Pattanayak and Shrivastava (1999) reported ~9–11% Fe content in Deccan basalts. The iron-rich clay minerals are produced from the weathering of iron-rich source rocks namely unaltered ferromagnesium minerals and Fe-rich oxyhydroxides (Das and Krishnaswami, 2007). The higher Fe

Table 8.3 Range of Al, Ti, Fe, Mn, Zn, and Pb in surface sediments along transects from Mahanadi to Pennar rivers.

Transect	Off river mouth	Al (%)	Ti (%)	Fe (%)	Mn (%)	Zn (ppm)	Pb (ppm)
1	Hooghly river mouth—North	Nd	Nd	Nd	Nd	Nd	Nd
2	Hooghly river mouth—South	Nd	Nd	Nd	Nd	Nd	Nd
3	Mahanadi river mouth—North						
4	Mahanadi river mouth—South	5.45–9.52	0.28–0.82	4.35–6.14	0.08–0.67	54.75–181.25	12.73–35.30
5	Vamsadhara river mouth	4.43–9.08	0.41–0.60	3.51–6.10	0.07–1.20	51.0–154.25	20.35–43.0
6	Between Godavari and Vamsadhara river mouths	4.79–10.75	0.33–0.85	2.95–5.91	0.05–0.58	60.25–154.0	12.45–45.05
7	Godavari river mouth	7.13- 8.57	0.63- 1.30	6.21- 9.70	0.10- 0.40	89.0–140.50	9.68–24.8
8	Krishna river mouth	7.18–9.03	0.76–1.90	5.74- 6.85	0.07- 0.28	99.0–141.50	8.65–23.43
9	Between Krishna and Pennar river	6.59–10.30	0.63–0.96	5.80–7.83	0.06–0.63	87.0–151.50	5.9–43.88
10	Pennar river mouth	6.86–8.85	0.63–0.84	5.32–8.80	0.15–0.27	72.75–129.25	12.58–31.05

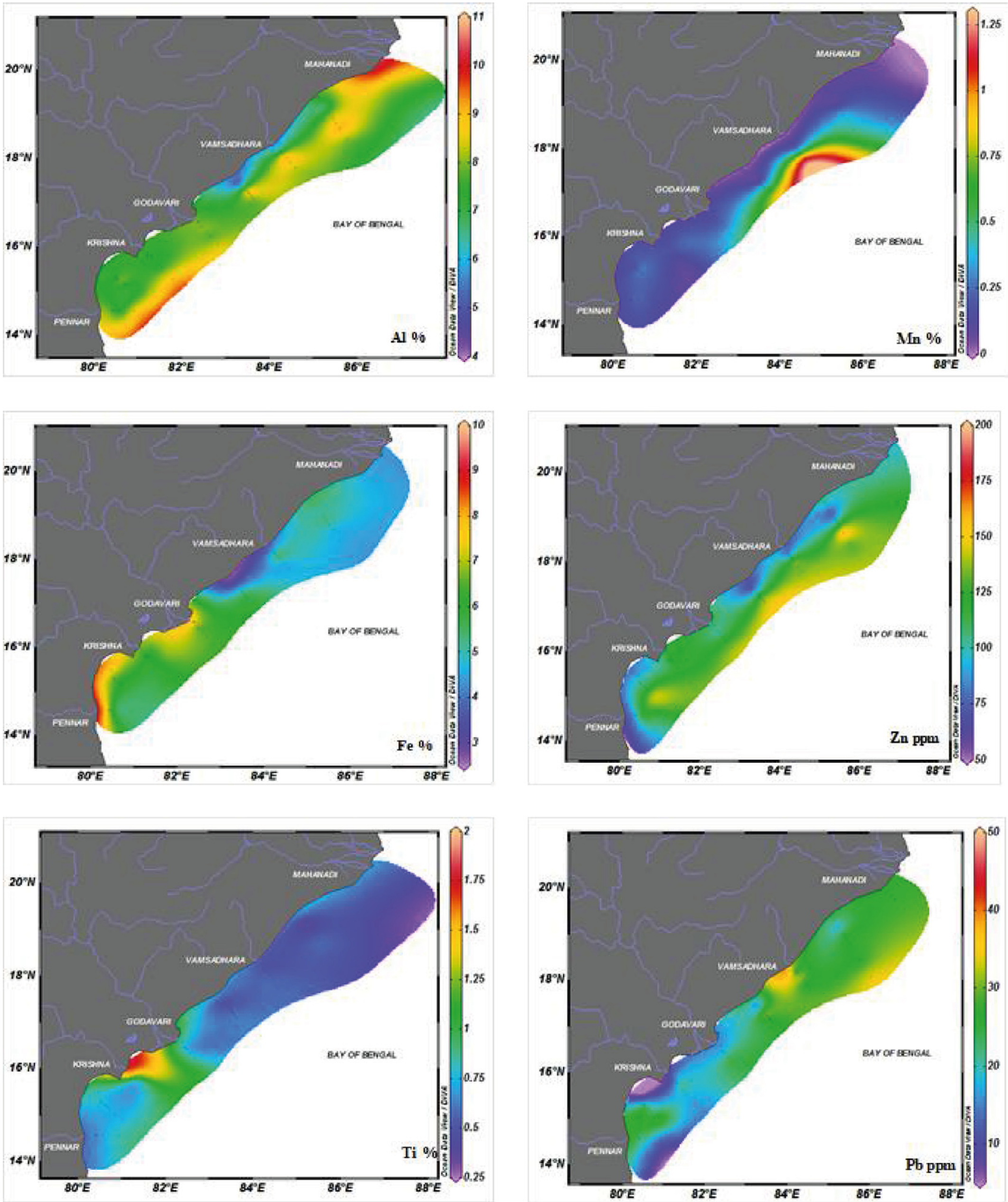

FIGURE 8.7

Distribution of a few major and trace elements in the surface sediments of the study area.

in cores off Godavari river mouth may have been contributed from the leaching of iron-rich sediments from "Red beds," dominant rocks near the Vishakapatnam coast. These red beds are formed under severe oxidizing conditions and are composed of ferric hydroxide. The red beds are usually associated with appreciable amounts of kaolinite explaining its higher concentration in the samples near the river mouth. Ti content in the samples was higher than the crustal PAAS value of 0.6%. However, Ti concentration in the sediments off Mahanadi and off Vamsadhara river mouths was lower indicating felsic source rocks. The higher Ti off Godavari, off Krishna and off Pennar river mouths as compared to off Mahanadi river mouth may have been contributed from the mafic source, that is, Deccan Trap basalt which is rich in titanium. The felsic rocks are the source of sediments off Mahanadi river while sediments off Krishna–Godavari river were mainly derived from Deccan basalts (Mazumdar et al., 2015). This is also supported by higher illite in the northern transects off Mahanadi and off Vamsadhara river mouths and high smectite content off Godavari, off Krishna, and off Pennar river mouths. The high Pb content also supported the source as felsic rocks in surface sediments off Mahanadi and off Vamsadhara river mouths and in the transect north off Godavari river mouth. Pb is usually hosted with rocks rich in feldspars (Prinz, 1967; Sensarma et al., 2016; Babeesh et al., 2017) such as granites. Pb is higher than crustal PAAS value of 20 ppm in most of the samples in the northern transects as well as few samples off Godavari, off Krishna, and off Pennar river mouths where illite is higher. Illite tends to adsorb Pb more readily into its structure explaining higher Pb enrichment in the sediments where illite was the dominant clay mineral. Several sorption experiments were carried out by researchers (Echeverria et al., 2005; Serrano et al., 2005) to understand the extent of Pb uptake on clay minerals. They revealed that due to cation exchange Pb tends to absorb on illite. However, smectite too is known to adsorb Pb into its lattice (Rybicka et al., 1995; Mhamdi et al., 2013) because of the negative charge on the surface and its shrink-swell property. This explains the appreciable Pb concentration in surface samples off Godavari, off Krishna, and off Pennar river mouths as well. In the majority of the samples, Mn and Zn concentrations were higher than crustal PAAS values of 0.09% and 85 ppm (Taylor and McLennan, 1985), respectively, indicating the presence of hydroxides.

The variations in average metal concentrations of the cores revealed that with increasing distance from the river mouth Fe, Ti, Mn, and Zn contents decreased indicating the abundant supply of these elements from lithogenous source rocks which after weathering are drained to the region through the peninsular river runoff. The chemical composition of marine sediments is the signature of materials derived from detrital, authigenic, and hydrothermal sources (Tripathy et al., 2014). Higher toxic waters probably lead to slightly higher metal enrichment in the samples close to the river mouth. However, average metal content is reduced off Mahanadi river mouth and at shallower water depth despite abundant terrestrial input as the dominant sand fraction in the core may not be able to preserve the metals within it. However, Al, Fe, Ti, Mn, Zn enrichment is noted in the upper few cm corresponding to higher clay value suggesting a metal association with the clay fraction. With a decrease in grain size trace element concentration increases reflecting an association with finer clay fraction due to its larger surface by volume ratio (Horowitz and Elrick, 1987; Burdige, 2006).

8.3.2 Gravity core sediments—sedimentary depositional environments and Holocene climate

The range and average values of sediment components, clay minerals, and metals are presented in Table 8.4A and zone wise average values in Table 8.4B for the gravity core GC-16 collected off

Table 8.4A Range and average values of sediment components, clay minerals, and metals in core GC-16.

Parameters	Range	Average
Sand (%)	0.43–30.11	3.49
Silt (%)	26.81–75.82	46.28
Clay (%)	22–66.16	50.23
Smectite (%)	0.0–21.89	5.98
Illite (%)	48.15–91.23	67.31
Kaolinite (%)	3.24–31.82	18.8
Chlorite (%)	0.0–25.1	7.91
Fe (%)	2.11–7.05	4.47
Mn (ppm)	229.5–698	412.14
Zn (ppm)	34.5–611.5	99.47
Pb (ppm)	0.02–9.59	2.61

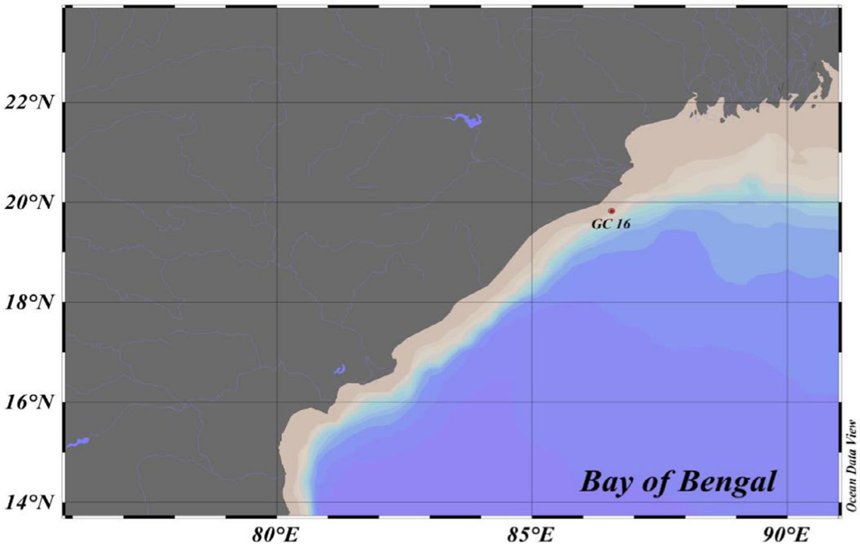

FIGURE 8.8

Map showing the core location.

Mahanadi river (Fig. 8.8). The rate of sedimentation (Fig. 8.9) computed using the ^{14}C dating method was 0.027 cm/yr from 200 to 100cm and 0.036 cm/yr from 100 cm to the surface of the sediment, indicated a relatively higher rate of sedimentation in recent years.

In the studied core sediment samples, the silt and clay together constituted over 96% with clay as the predominant sediment component. Based on the distribution of sediment components, clay minerals and metals the sediment core from bottom to the surface was divided into five zones they are, zone A to

Table 8.4B Average values of sediment components, clay minerals, and metals of zones in core GC-16.

Zone	Sand (%)	Silt (%)	Clay (%)	Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Fe (%)	Mn (ppm)	Pb (ppm)	Zn (ppm)
E	1.65	45.61	52.73	13.75	56.72	25.41	4.12	5.54	426.11	0.29	70.77
D	2.06	42.54	55.41	14.89	57.63	23.45	4.03	5.56	424.50	3.55	98.09
C	8.76	41.31	49.93	5.13	64.23	20.73	9.91	3.47	369.83	0.70	139.73
B	1.20	44.04	54.77	2.06	75.12	14.85	7.97	4.12	352.23	2.89	85.20
A	2.06	52.76	45.17	0.75	75.16	14.20	9.89	4.24	450.03	4.49	88.83

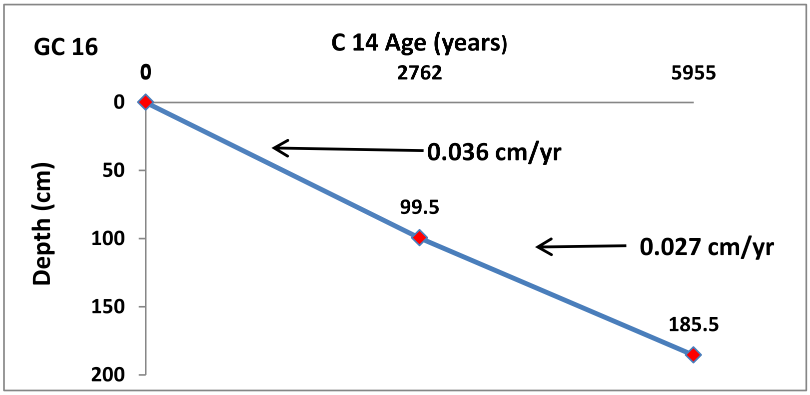

FIGURE 8.9

Age–depth curve of core GC-16.

zone E. The sand percentage was higher than the core average in zone C, silt was higher in zone A and clay was higher in zones B, D, E, and C very close to the average value (Table 8.4A–B). The variation observed in sediment components suggested the deposition of sediment in fluctuating depositional environments. The presence of coarser sediment in the sample indicates high energy environments and finer sediment suggests quiet hydrodynamic conditions (Fernandes and Nayak, 2009, 2020). The hydrodynamic conditions and sediment particle size control the rate of sedimentation at a given location. The types of rocks present in the catchment area, type of weathering, topography (Riebe et al., 2015), drainage network, climatic conditions, and monsoon intensity control the sediment size. The sediment is redistributed based on size upon entering the ocean which is controlled by the hydrodynamic conditions. The high clay content in the upper portion of the core reveals sediment deposition in quiet environments with a high rate of sedimentation.

Among the clay minerals, illite was the most abundant (avg. ~67%) in the core sediments being relatively resistant (Biscaye, 1965). As stated earlier high illite off Mahanadi river mouth indicates supply from felsic rocks, which belong to the Archean–Proterozoic gneissic complex (Mazumdar et al., 2015) and as K-feldspars are easily weathered to clay minerals (Chen et al., 2010). The smectite and chlorite were low in the sediments. The chemical weathering of mafic minerals present in the gneiss and charnockites (Bastia et al., 2020) must have contributed to smectite and chlorite was unstable in humid tropical conditions. So, the weathered materials from the catchment area and transported through the Mahanadi river was the major supplier of these minerals at the core location. Besides, illite was also contributed through Ganges and Brahmaputra as they are transported and redistributed by turbidity currents (Kolla and Rao, 1990; Bejugam and Nayak, 2016b) along the western Bay of Bengal. The distribution of clay minerals provides information on depositional environments as it is controlled by energy conditions (Rao et al., 1988; Moore and Reynolds, 1989; Liu et al., 2010). The smectite is finer in size and therefore can remain in suspension for a longer time and further even weak currents could transport it. Salinity is low in waters near the river mouth. Compared to smectite, illite has coarser size and more stable than smectite under less saline conditions explaining the higher illite content under

Table 8.5 Geochronology and Holocene climate periods.

Zone	Depth (cm)	Characteristic features	Rate of sedimentation (cm/yr)	Age (cal yr. BP)	Holocene climatic periods
E	0–26	High clay, smectite, kaolinite, Fe, Mn, Zn	0.036	0–708 (2014–1306 AD)	Recent global warming and retreating Little Ice Age
D	26–58	High clay, smectite, kaolinite, Fe, Mn, Zn, Pb		708–1597 (1306–417 AD)	Medieval warm period also called Little Climatic Optimum
C	58–100	High and fluctuating clay and smectite		1597–2762 (417 AD–748 BC)	Roman warm and cold period
B	100–122	High and fluctuating silt and illite; low Fe, Mn, Zn	0.027	2762–3097 (748–1083 BC)	Sub-boreal cold climatic period
A	122–184	High silt, illite, Mn, Pb		3097–5955 (1083–3941 BC)	Sub-boreal cold climatic period

high energy conditions near the river mouth. The presence of predominant illite at the core location off Mahanadi river mouths indicates high energy conditions prevalent during the time of deposition.

Further, illite and smectite contents present in sediments were related to supply of weathered material from Himalayan regions through Hoogly river and peninsular region by peninsular Indian rivers, respectively (Kolla and Rao, 1990; Raman et al., 1995; Reddy and Rao, 2001) concerning intensification of NE and SW monsoons. The clay mineral distribution in the core indicated high illite values in zones A and B, kaolinite in zones C, D, and E, smectite in zones D and E, and chlorite values in zones A, B, and C than the average. High illite and chlorite in zones A and B indicate their formation in cooler and dryer climatic periods and represent high latitude regions while high smectite and kaolinite in zones D and E indicate warmer and wetter climates (Griffin et al., 1968) with zone C representing intermediate.

In zone A higher than the average illite associated with silt and lower than the average smectite associated with clay suggested their deposition in relatively higher hydrodynamic conditions. Higher than average illite and chlorite (Table 8.4B) were noted in zone B and the kaolinite content was overall lower than average in both zones A and B. Illite associated with silt (Table 8.5) in these zones must have deposited in relatively high energy hydrodynamic conditions. The zones A and B varying from 5955 to 2762 cal yr B.P. largely represent the sub-boreal climatic period of northern Europe, between the Atlantic and sub-Atlantic stages about 5000–2800 years ago. Nagasundaram et al. (2020) have reported the intense weakening of the SW monsoon during the sub-boreal period in the Bay of Bengal. The reduced terrigenous material supply because of the weak SW monsoon to the study area during the period possibly was responsible for the reduced rate of sedimentation. The increased hydrodynamic regime in Galicia during this climatic period was observed earlier by Rocha et al. (2006). High sand content (8.76%) and clay (49.93%), higher than average kaolinite, chlorite (Table 8.4B), and smectite with lower than average silt and illite in zone C from 2762 to 1597 cal yr B.P. largely coincided with the Roman Warm and cold periods. High sand and clay possibly indicate change over from cold to warm climate and changed hydrodynamic conditions from high energy to low possibly facilitating the deposition of high clay and smectite in quiet hydrodynamic conditions. During the Roman Warm Period increased rainfall in the Indian Subcontinent was documented by Pothuri et al. (2014) and Pothuri (2017). The enhanced SW monsoon might have facilitated the chemical weathering of mafic rocks and helped in the formation of smectite. In zone D, higher than average clay, smectite, and kaolinite (Table 8.4B) and low silt, illite, and chlorite represent the Medieval warm period (Table 8.5). Easterbrook (2016) recorded 1°C warmer global temperature than recent temperature and Sridhar (2009) and Suokhrie et al. (2018) reported strengthening monsoon during the Medieval Warm Period in the Bay of Bengal. In zone E, higher than the average smectite, kaolinite (Table 8.4B) along with clay and, low illite, chlorite and silt suggested increased chemical weathering of mafic source rocks in the presence of warm and wet climate during the recent global warming period.

To identify the source, processes and conditions of deposition the metal content in sediments are an important proxy (Chakrapani and Subramanian, 1990; Raj and Jayaprakash, 2008; Pattan et al., 2008). Among the studied metals in the core, Fe values were high in zones D and E; Mn in A, D, and E; Pb in A, B, and D; and the value of Zn in zone C was higher than average. In zone A, high Mn and Pb are associated with high silt and Illite with low content of Fe and Zn associated with clay. Lower than average Fe, Mn, Zn, and fluctuating Pb were observed in zone B. In zone C, Zn content was high along with high sand percentage. Higher than average Fe, Mn, Zn, Pb was associated with high clay, smectite, kaolinite, and low silt, illite and chlorite in zone D. In zone E higher than average Fe and Mn were associated with high clay, smectite, and kaolinite. In zones A and B presence of low Fe, Mn, and Zn indicated the reduced release of material from the Peninsula rivers controlled by the reduced intensity of the SW monsoon. In zones D, E, and to some extent in zone C high Fe, Mn, and Zn support higher supply regulated by warm and wet climate and enhanced SW monsoon.

High silt, illite, and Mn with lower than average clay, kaolinite, smectite, Zn, and fluctuating Fe regulated by the cold and dry climate were responsible for lower sedimentation rate obtained from 186 to 100 cm. In the upper 100 cm of the core high clay, kaolinite, smectite, Fe, Mn, Zn with low silt, illite, chlorite coincided with the high rate of sedimentation regulated by warm and wet climate and intense SW monsoon. The signatures of the proxies used in the present study namely sediment components, clay minerals, and metals were effective in understanding change in sediment supply, depositional environments, and sedimentation rates which were regulated by the cold and dry, and warm and wet climate and intensity of SW and NE monsoons.

8.4 Learning and knowledge outcomes

The source, transportation history, climatic conditions at the time of sediment deposition and intensity of monsoons were studied using proxies namely grain size, clay minerals, and metals in the western Bay of Bengal which is fed by sediment flux from Ganges–Brahmaputra, Mahanadi, Godavari, Krishna, Cauvery, Irrawaddy, and Pennar rivers. The study on surface and multicore sediments reveals that among the sediment components clay is the dominant sediment fraction. However, higher sand was observed in sediments in shallow water regions due to the closer proximity to the river mouth. Higher sand content in shallow water regions and higher clay content in deeper water regions indicate transport direction from coast to offshore and material supply from the rivers to the bay. Also, grain size decreases from off Hooghly river mouth in the north, through off Mahanadi, off Vamsadhara, off Godavari, and off

Krishna to off Pennar river mouth regions in the south indicates high energy conditions prevalent off Hooghly and Mahanadi rivers which facilitates the deposition of relatively coarse grain sediments and prevents the accumulation of fine-grain sediments near the river mouth. Among the clay minerals, the smectite was dominant in samples off Godavari, Krishna, and Pennar rivers formed as a product of chemical weathering under humid tropical conditions and finds its source from the Deccan Trap basalts and associated black cotton soils. Illite was higher in sediments off Hooghly, Mahanadi, and Vamsadhara rivers formed as a product of mechanical weathering under arid cold climatic conditions by the alteration of muscovite mica which is a dominant mineral in the Himalayan region and illite may have drained through the Ganges–Brahmaputra rivers. Also, rocks from the Eastern Ghats rich in potash feldspar may have undergone alteration and provided illite to the region. A loss of energy southward could have prevented the downward transport of illite-rich sediments. Appreciable kaolinite content is probably from the Archean granites and gneisses and from red beds which is a dominant rock type along the coastal areas of Godavari river. Fe and Ti concentrations are higher in sediments off Godavari and Krishna derived from mafic-rich source rocks as well as from the red beds which are rich in ferric oxide.

The variation of proxies studied along the length of the gravity core represents changing Holocene climatic oscillations. The lower two zones of the core largely coincide with the sub-boreal climate periods during which dry conditions favored increased physical weathering of felsic source rocks. Zone C represents the intermediate climate conditions and coincides with the Roman cold–warm period, while, toward the surface of the core, the two zones represent warm periods of the Medieval Warm Period and recent global warming. During these periods a significant increase in warm–wet conditions must have facilitated the leaching of mafic rocks.

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