



^{210}Pb dating of recent sediments from the continental shelf of western India: factors influencing sedimentation rates

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Abstract Several cores from the continental shelf of the Arabian Sea along the Indian Coast were investigated for change in sedimentation rates duly constrained for chronology based on ^{210}Pb and ^{137}Cs dating techniques. The emphasis was to look for spatial and temporal variation in the sedimentation rate along the continental shelf of eastern Arabian Sea between Goa to Kochi for water depth ≤ 150 m. This study showed varying sedimentation rates in coastal and distant sediment cores. Both ^{210}Pb and ^{137}Cs dating techniques showed comparable sedimentation rate in most sediment cores. The sedimentation in the continental shelf region of the coastal Arabian Sea is primarily controlled by discharge of sediments from rivers during Indian summer monsoon. Increased sedimentation rate from the north (off Goa) to the south (off Kochi) was triggered by high riverine flux and longshore sediment transport.

Keywords Sedimentation rate · ^{210}Pb dating · ^{137}Cs · Western Indian coast · GEOTRACES

Introduction

The western Indian continental shelf (WICS) with an area of nearly 310,000 km² (Manjunatha and Shankar 1992) is wider near Ratnagiri, Maharashtra and narrower towards south near Kochi, Kerala, with width ranging from 130 to 60 km and thus classified as Stable Atlantic type margin (P. Rao and Wagle 1997). The shelf breaks at 199 m in the northern and 80 m in the southern part of the eastern Arabian Sea. The WICS has distinct sediment type such as clastic clays and relict sand on the inner and the outer shelf respectively (Nair and Pylee 1968) along with silty clays consisting of terrigenous and biogenic components found in the continental slope. Between 7 and 17°N, the continental shelf and slope consist of authigenic green clays (verdine and glaucony) and its origin attributed to the iron contributed by numerous small rivers (Thamban and Rao 2000). The central and south-western continental margin of India is endowed with river derived clays with a trivial contribution from the aeolian fraction (Naidu et al. 1985; V. P. Rao and Rao 1995). The sediment discharge from Indian rivers to the northern Indian Ocean is 1.2×10^{12} kg year⁻¹ (Chandramohan et al. 2001). The westward flowing rivers such as Narmada, Tapi, Nethravathi and Periyar and those draining the Western Ghats (Vashishti, Kajli and Sukh) are the major detrital contributors to the Arabian Sea (Goswami et al. 2012). Various rivers draining through the Western Ghats vary in length between 85 to 250 km, and flow through steep slopes of the mountain ranges covering an area of about 54,000 km², thereby discharging about

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95.58 km³ of water annually into the eastern Arabian Sea (K. L. Rao 1979). The particulate flux to the Arabian Sea from rivers and atmosphere was reported to be ~ 500 and 100 Tg year⁻¹ respectively (J. D. Milliman et al. 1984; Sirocko and Sarnthein 1989). Significant decline in the sediment flux from the Indus (from ~ 250 to ~ 10 Tg year⁻¹) and other rivers has been observed and caused due to the construction of numerous dams along their pathway (Garzanti et al. 2005) resulting in reduction of the annual sediment flux to the Arabian Sea ~ 30 Tg year⁻¹ (J. Milliman and Farnsworth 2013).

²¹⁰Pb dating

The ²¹⁰Pb concentration in surface air is primarily due to ²¹⁰Pb sources, transport and deposition mechanism which is driven by atmospheric circulation and precipitation (Preiss et al. 1996). ²²²Rn, a daughter product of U-series decay, is the main source of ²¹⁰Pb, which escapes from the earth's surface with the mean emission rate of ~ 1 atom cm⁻² s⁻¹ from ice-free continental regions. The ice-covered regions are not considered as major ²¹⁰Pb source, as ²²²Rn does not escape through ice easily. The ²¹⁰Pb emission rate from the oceanic region is almost 100 times lower than terrestrial regions (Turekian et al. 1977). The ²¹⁰Pb fallout rates in the northern hemisphere oceanic region range from 0.003 to 0.35 mBq m⁻³, and for southern hemisphere oceanic region, it ranges between 0.012 and 0.12 mBq m⁻³ (Preiss et al. 1996). In the Indian subcontinent, the ²¹⁰Pb concentration in surface air decreases from north to south of the peninsula (1 to 0.5 mBq m⁻³). High homogenous ²¹⁰Pb concentration has been observed in northern India, while decrease along the peninsula is attributed to the increased marine influence surrounding the peninsula (Preiss et al. 1996). The ²¹⁰Pb air-surface deposition flux in the Indian subcontinent shows a decreasing flux gradient from the north to south (182 to 85 mBq m⁻² year⁻¹) (Joshi et al. 1969). The ²¹⁰Pb dating is primarily based on ²¹⁰Pb fallout, and it has been found on a global scale that there is a consistent west to east increase in ²¹⁰Pb fallout within the major continents (Appleby 1997).

For decadal to century timescales, paleo-environmental reconstruction is generally supported by estimation of the sedimentation rates with the help of ²¹⁰Pb, due to its short half-life of 22.3 years duly supported by ¹³⁷Cs. ²¹⁰Pb isotope is a naturally occurring radionuclide formed as a decay product of ²³⁸U decay

series. The ²³⁸U present in the Earth's crust decays to ²²⁶Ra, followed by ²²²Rn, which is a gas that escapes to the atmosphere and further decays to ²¹⁰Pb. This ²¹⁰Pb in the atmosphere, is brought back to the Earth's surface via precipitation or snowfall and again introduced to the marine and lake systems and is known as unsupported or excess ²¹⁰Pb. The ²¹⁰Pb is also formed within the sediment as a decay product of ²³⁸U, which is incorporated into the mineral grain and is defined as supported ²¹⁰Pb. Among the two sources, it is the unsupported or excess ²¹⁰Pb which decays. To estimate the unsupported ²¹⁰Pb, whose decay is used to ascertain the sedimentation rate, activity of ²²⁶Ra (parent of ²¹⁰Pb) is subtracted from the total ²¹⁰Pb activity, with an assumption that both supported ²¹⁰Pb and ²²⁶Ra are in secular equilibrium (Appleby and Oldfield 1992; Pfeiffer Madsen and Sørensen 1979).

Atmospheric cesium-137 distribution and fallout

¹³⁷Cs is an artificial radionuclide with a half-life of ~ 30 years. Widespread global dispersal of ¹³⁷Cs to the environment resulted due to the thermonuclear weapon tests since 1952 (Perkins and Thomas 1980). During such tests, the ¹³⁷Cs was injected to the stratosphere, and it circulated globally (Longmore 1982). The fallout of ¹³⁷Cs is strongly related to local precipitation pattern and deposition rates (Longmore 1982). The maximum atmospheric ¹³⁷Cs concentration was found during 1963 or 1964 (Robbins and Edgington 1975), and thus ¹³⁷Cs activity maxima in a sediment core profile signify the particular discharge events and hence the time of maximum fallout. Depending on latitude, on a global scale, the bomb-derived ¹³⁷Cs fallout ranges between 160 and 3990 Bq m⁻² (Garcia Agudo 1998). Isolated incidents of accidental ¹³⁷Cs dispersion into the atmosphere led to the contribution of ¹³⁷Cs into the atmosphere and these peaks have been noticed in the sediment core. Till date, maximum ¹³⁷Cs concentration observed in the atmosphere was during 1963 and 1964 attributed to nuclear tests, whereas records of major accidental fallout of ¹³⁷Cs such as Chernobyl Accident (CA) and Fukushima Daiichi (FD) nuclear power plant accident have also been reported (Butler 2011; Chino et al. 2011). CA took place at Chernobyl reactor, USSR, on April 26, 1986 for which the first detection of radioactivity in the atmosphere was observed in Sweden and subsequently in Japan on May 3, 1986 (Aoyama et al. 1986). The ¹³⁷Cs fallout originating from Chernobyl affected many

areas in Europe as well leading to an increase in bomb-derived inventory of ^{137}Cs by several orders of magnitude at various locations (Mabit et al. 2008). *FD* accident caused by tsunami as a result of Tohoku earthquake on March 11, 2011 resulted in enormous emission of radionuclides to the atmosphere (Butler 2011; Chino et al. 2011). During the accident, ^{137}Cs dispersal was accompanied by ^{131}I and model-based budget analysis showed that nearly 13% and 22% of ^{131}I and ^{137}Cs respectively deposited over land in Japan, while the rest of the proportion got deposited over the ocean (Morino et al. 2011).

The industrial era witnessed both natural and human-induced climate perturbations which encouraged the paleoclimate community to conduct high-resolution study of climate. ^{210}Pb dating technique found potential applicability in reconstructing the climate of the last two centuries. The sedimentation rates for the ^{210}Pb -dated sediment cores collected off Gujarat and Bombay (21°N) at water depth > 200 m indicated varying sedimentation rates from 0.33 to 1.41 mm year⁻¹ (Somayajulu et al. 1994). The sediment deposition rates along the continental margins of the Arabian Sea, based on ^{210}Pb , ^{137}Cs and ^{14}C techniques, showed 0.5–6.6 mm year⁻¹ up to core depth of ≤ 10 cm; later, it varied between 0.04 and 1.3 mm year⁻¹ for depths > 10 cm (Somayajulu et al. 1999). Recent study on mudflats from the central west coast of India shows low sedimentation rate of 0.13–2 cm year⁻¹ until 1980 followed by an increased sedimentation rate of 1.2–2 cm year⁻¹ (K. T. Singh et al. 2014).

The present study attempts to decipher the sedimentation rate using ^{210}Pb along the continental shelf of the eastern Arabian Sea between Goa to Kochi for water depth ≤ 150 m. Additionally, ^{137}Cs -based sedimentation rates were also derived, which provide average sedimentation rate for the period after 1963 and can be useful for locations where ^{210}Pb profiles do not show consistent decay due to anomalous reasons. The derived sedimentation rates would pave way for future studies on paleo-environmental studies pertaining to coastal pollution, eutrophication and productivity.

Study area

Arabian Sea is a unique region experiencing strong upwelling during Southwest (SW) monsoon with negative water balance (evaporation exceeds precipitation) and runoff (Naqvi et al. 2006). Strength and intensity of

the SW monsoon play a crucial role in controlling the inter-annual variability of organic carbon flux in the northern Indian Ocean. Based on sediment traps deployed in the northern Indian Ocean (1000 m above the seafloor), average annual fluxes of organic carbon were estimated to be > 50 g m⁻² year⁻¹ and < 27 g m⁻² year⁻¹ in the western and central part of the Arabian Sea respectively (Ramaswamy and Nair 1994). The entire process of particle transport, emplacement, removal and preservation in the seabed is defined as sedimentation (McKee et al. 1983). The sedimentation rate of a particular region depends on the circulation pattern and environmental conditions at the site of deposition (Rao and Wagle 1997). Marine sediment cores supported by chronology have been extensively used to reconstruct past changes in climate and circulation on millennial, centennial and decadal time scales. Chronological tools as appropriate to various timescales have found its applicability in understanding the paleoclimatic perturbations. Radiocarbon dating (^{14}C) has found extensive application to ascertain the age of deep-sea sediment cores for the reconstruction of millennial to centennial-scale climate and oceanic processes, but extends only to ~ 50 ka and is not applicable for last 250 years due to anthropogenic effects. Radiocarbon dating of planktonic foraminifers from Saurashtra coast (water depth, 280 m; sedimentation rate, 1 mm year⁻¹), Mangalore coast (water depth, 600 m; sedimentation rate, 0.08 mm year⁻¹) (Bhushan et al. 2001), Thiruvananthapuram coast (water depth, 499 m; sedimentation rate, 4.5–8.7 cm kyr⁻¹) (V. P. Rao et al. 2010), central coast (water depth, 1682 m; sedimentation rate, 1.83–12.99 cm kyr⁻¹) and south-eastern coast (water depth, 2680 m; sedimentation rate 3.13–13.9 cm kyr⁻¹) (Agnihotri et al. 2003) in the Arabian Sea show varying sedimentation rates. Study based on ^{14}C dating of carbonised wood samples retrieved from 14°N and 74°E yielded a sedimentation rate of 0.4–0.7 mm year⁻¹ (Nambiar and Rajagopalan 1995). Active (Banerji et al. 2016) and relict mudflats (Banerji et al. 2015, 2017) of southern Saurashtra coast have yielded sedimentation rate of 0.23–0.14 mm year⁻¹ and 0.26–0.3 mm year⁻¹ respectively. Based on these geochronological data, paleo sea level, paleoclimate and paleo-productivity processes have been reconstructed on millennia and centennial time scales.

There have been numerous studies addressing the estimation of sedimentation rates in the off-shore region of the Arabian Sea (Nambiar et al. 1991; K. T. Singh

et al. 2014; Somayajulu et al. 1999). Most of the studies have been carried out in the open oceans or coastal regions with water depths ≥ 200 m. During the last century, various industrial development led to nutrient supply in the estuarine and coastal environments causing coastal eutrophication along the western Indian coast (Martin et al. 2011). But the reconstruction of paleo-environmental condition requires high-resolution climatic data preferably on annual to sub-annually resolved coastal archives. The shallow coastal areas with higher sedimentation rates have proved a great potential for acting as a climatic archive for recent anthropogenic effects (Smith and Schafer 1987). Thus, reconstruction of the high-resolution variability of the coastal environment due to natural and/or anthropogenic activities need to be supported by sedimentation rates and thereby chronology. Although, there exist estuarine and mudflat sedimentation rates but they are sparse and region-specific. This study is an effort to understand variable sedimentation rates which can have implications to the sediment depositional environment and circulation pattern and thereby its comparison with the previously reported sedimentation rates along the coastal region of western Indian coast between Goa and Kochi can provide very useful information.

Material and methods

To decipher the changes in the sedimentation rates along the continental shelf in the coastal Arabian Sea, an oceanographic cruise SM-29 onboard ORV *Sagar Manjusha* was undertaken during October 2013 beginning from Goa to Kochi covering several transects. During this cruise, several sediment cores from different water depths were collected with the help of gravity corer (Fig. 1). The gravity coring device used for collection of sediment core in this study consists of core tubes and an upper assembly which provides support for the drive weights. The corer is lowered to the ocean floor by gravity, and the sediment sample is retained in the core tube by core catcher. (Papucci 1997). As the width of the continental margin of western India varies between 130 and 60 km (P. Rao and Wagle 1997), sediment cores were collected at 1° latitudinal difference at a distance of 60 km from the coast. The cores collected from near coast were from water depth < 20 – 35 m, while the cores collected away from the coast were at water depth > 40 – 100 m. Three cores each from

offshore and near coast locations were chosen for this study. The details of these cores are provided in Table 1.

All the six sediment cores were subsampled at 1-cm interval using a non-metallic knife. Samples were oven-dried at 80°C and finely crushed for homogenisation using coning and quartering procedure (Rubio and Ure 1993). Nearly 3 g of dry homogenised samples were sealed in a plastic vial and stored for at least 15 days to enable ^{226}Ra and ^{222}Rn in each sample to establish radioactive equilibrium (Hamilton et al. 1994). The gamma counter used for ^{210}Pb dating was a germanium detector made of high-purity germanium (HPGe) crystal mounted on a vacuum chamber for protection from moisture and cooled by liquid nitrogen. The packed samples were placed in the high-purity germanium detectors (HPGe coaxial 16×40 mm well-type detector, Canberra Industries, CT, USA). The ^{137}Cs , ^{210}Pb and ^{226}Ra of the samples were assayed using a non-destructive gamma counting technique (Cutshall et al. 1983).

The samples were counted for 3 days to determine the activities of ^{137}Cs , ^{210}Pb and ^{226}Ra . The ^{210}Pb excess was estimated by subtracting ^{226}Ra from total ^{210}Pb activity with an assumption that ^{210}Pb supported is in secular equilibrium with ^{226}Ra (Han et al. 2011). The sedimentation rate was determined by applying constant flux:constant sedimentation rate (CF:CS) model of ^{210}Pb dating (Appleby and Oldfield 1992). The average sedimentation rates for the cores have been estimated by taking least-square fitting of all data points measured for ^{210}Pb activity at various depths for each of the cores (Table 2).

For Al measurement, nearly 0.3 g of bulk, dried crushed sediment sample was subjected to closed digestion (in microwave digestion system) by treating with concentrated acids (HCl, HF and HNO_3) using standard protocol (Dalai et al. 2004). The dissolved solution was taken in 2% HNO_3 medium and made up to 50 ml. Following standard procedure, Al was measured using *Jobin Yvon* ICP-AES (Dalai et al. 2004; S. K. Singh 1999). The analytical precision of measurement of Al was found to be better than $\pm 5\%$.

Results and discussions

Due to soil erosion, deforestation and changes in land use patterns in recent years, there has been increase in the suspended matter derived from rivers. Nearly 65% of 24.8 billion tons of suspended sediment added

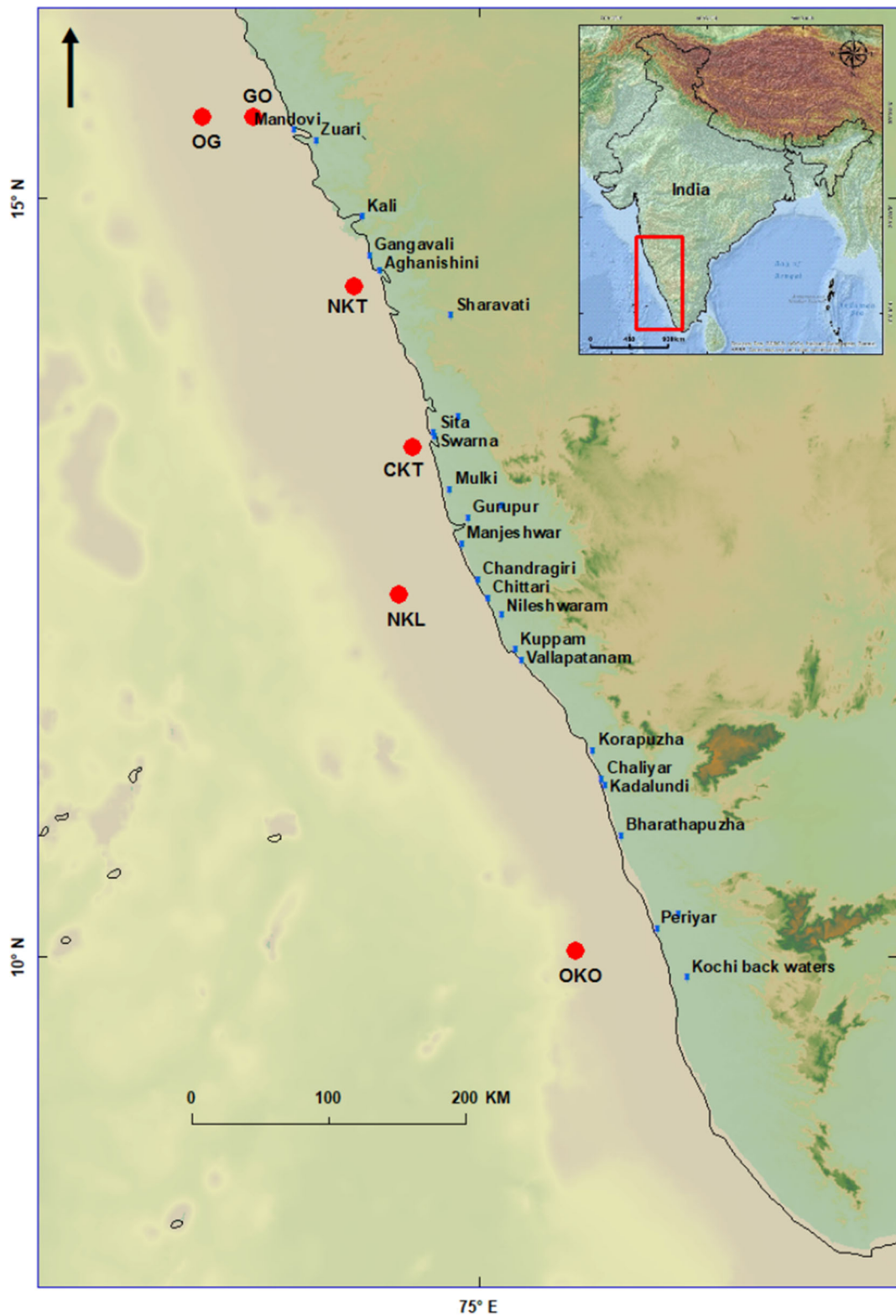


Fig. 1 Sediment core locations raised during Sagar Manjusha (SM-29) cruise between Goa and Kochi (rivers are marked with blue dot)

Table 1 Details of the sediment cores collected using gravity corer from the continental margin of the eastern Arabian Sea

Sr no.	Core ID	Latitude (°N)	Longitude (°E)	Core length (cm)	Water depth (m)
1.	SM-29/13/03 (GO)	15.53	73.53	88	30
2.	SM-29/13/07 (NKT)	14.41	74.19	90	35
3.	SM-29/13/09 (CKT)	13.35	74.57	28	23
4.	SM-29/13/05 (OG)	15.53	73.19	32	40
5.	SM-29/13/12B (NKL)	12.38	74.48	21	86
6.	SM-29/13/14 (OKO)	10.04	75.64	50	108

annually by rivers is from anthropogenic sources (Frankel 1995). Various factors such as runoff, relief, geology, basin area, temperature and human influence play a significant role in controlling the sediment transport by rivers to the coastal regions (Chakrapani 2005). Numerous studies have mostly used radiocarbon ages for estimating the sedimentation rates for addressing the past climate reconstruction exclusively focussing on past few centuries to millennial time scales from the sediment cores raised from the continental shelf and offshore regions of the Arabian Sea with water depths ≥ 200 m (Agnihotri et al. 2002, 2008; Sinha et al. 2011; Meloth Thamban et al. 2007). However, limited studies have addressed the anthropogenic impacts along the western Indian coast by ascertaining the sedimentation rates for the last few decades to century. ^{210}Pb dating technique and ^{137}Cs thus are promising tool for assigning chronology on decadal to century scale environmental changes. The sediment cores collected during the cruise were divided into two groups as a function of distance from the coast i.e. near coastal and distant. The details of the sedimentation rates and year of deposition of the sediment at selected locations along the western continental margins have been discussed. During the SM-29 cruise, nearly three shallow water sediment cores

(SWSC) were retrieved from the continental shelf of western India viz. Goa (GO), North Karnataka (NKT) and Central Karnataka (CKT) with water depths ranging $< 20\text{--}35$ m. The sediment cores collected from water depths > 35 m but restricted to 100 m were considered as deep-water sediment core (DWSC). Nearly three sediment cores with water depths > 35 m were collected from off Goa (OG), Northern Kerala (NKL) and off Kochi (OKO).

Sedimentation rates for shallow water sediment cores [water depth $< 20\text{--}35$ m]

The sediment cores GO, NKT and CKT are located ~ 20 km perpendicularly away from the Mandovi and Zuari Rivers of Goa, Kali and Gangavali rivers of northern Karnataka and Suvama and Sita rivers of Central Karnataka that are debouching in to the Arabian Sea (Fig. 1). $^{210}\text{Pb}_{(\text{xs})}$ activities in the sediment cores GO, NKT and CKT could be observed up to a depth of 21 cm (1.77 to 142.7 mBq gm^{-1}), 26 cm (44.3 to 208.4 mBq gm^{-1}) and 28 cm (4.82 to 129.8 mBq gm^{-1}) respectively. Among the SWSC, maximum $^{210}\text{Pb}_{(\text{xs})}$ activity is observed in NKT, while lowest $^{210}\text{Pb}_{(\text{xs})}$ activity is estimated in CKT sediment core. The ^{137}Cs activity for GO, NKT and CKT

Table 2 Sedimentation rates based on $^{210}\text{Pb}_{(\text{xs})}$ and ^{137}Cs for the sediment cores collected during Sagar Manjusha Cruise (SM-29)

Station	Sedimentation rate (cm year^{-1})			^{137}Cs peak depth corresponding to 1963 AD
	$^{210}\text{Pb}_{(\text{xs})}$	Average	^{137}Cs	
GO	0.16–0.38	0.26	0.35	17.5
NKT	0.25–0.74	0.43	0.51	7.5
CKT	0.10–0.90	0.21	0.15	7.5
OG	0.10–0.36	0.23	0.19	9.5
NKL	0.30–0.32	0.39	0.39	19.5
OKO	0.33–0.69	0.43	0.61	30.5

ranges from 82.6 to 161.4 mBq gm⁻¹, 121 to 159 mBq gm⁻¹ and 88.5 to 98.7 mBq gm⁻¹ respectively. The GO core shows varying sedimentation rates ranging from 0.16–0.38 cm year⁻¹ with the highest sedimentation rate (0.38 cm year⁻¹) at depth range of 20.5–41.5 cm, while the slowest sedimentation rates (0.16 cm year⁻¹) were observed at 17.5–20.5 cm. The average sedimentation for this core was found to be 0.26 cm year⁻¹ (Fig. 2).

Considering surface as the year of collection, the sediment core GO with length of ~88 cm represents a depositional history of 1742–2013 AD. During 1742–1918 AD (88–20.5 cm), the sedimentation rate was nearly 0.38 cm year⁻¹ followed by a gradual decrease in the sedimentation rate (0.16 cm year⁻¹) between 1918 and 1937 AD (20.5–17.5 cm). An increase in the sedimentation rate (0.20 to 0.28 cm yr⁻¹) was observed post 1937 AD which continued until 2013 AD (year of core collection). The sediment core NKT (~90-cm length) represents a deposition history since 1692 AD assuming a constant sedimentation rate of 0.25 cm year⁻¹ beyond 26 cm. Select depths from bottom of the core would be used for other dating technique, as ²¹⁰Pb can only be used for the recent sediments deposited in last two centuries. Considering the limitation of the ²¹⁰Pb age estimation, slowest sedimentation rate of 0.25 cm year⁻¹ has been observed until 1988 AD (15.5 cm) (Fig. 2). Following this, an increase in the sedimentation rate of 0.74 cm year⁻¹ has been observed until 2010 AD (7.5 cm). However, the top 8 cm of the core shows unexpected variation in ²¹⁰Pb_(xs) activity, possibly due to bioturbation or sediment mixing during core retrieval. The CKT sediment core (~28-cm length) recorded a deposition history since 1898 AD. A slow sedimentation rate of 0.10 cm year⁻¹ persisted between 1898 and 1958 AD (30–21.5 cm) with a marginal increase in the sedimentation rate after 1958 AD that continued until 1996 AD (14.5 cm). Post 1996 AD, an extensive increase in the sedimentation rate of 0.90 cm year⁻¹ prevailed until 2013 AD.

Sedimentation rates for deep-water sediment core [water depth > 35 m < 100 m]

The deep-water sediment cores viz. OG, NKL and OKO are located ~60 km from the Indian coast. The ²¹⁰Pb_(xs) activities for OG, NKL and OKO ranged from 3.48 to 40.2 mBq gm⁻¹, 20.6 to 81.0 mBq g⁻¹ and 0.37 to 13.5 mBq gm⁻¹ at depths of ~27 cm, 20 cm and 22 cm respectively. The maximum and minimum

²¹⁰Pb_(xs) activities are observed in OG and OKO sediment cores. The ¹³⁷Cs activities for OG, NKL and OKO ranged from 58.0 to 76.0 mBq gm⁻¹, 74.6 to 80.5 mBq gm⁻¹ and 67.6 to 85.6 mBq gm⁻¹ respectively. The OG sediment core showed varying sedimentation rates ranging from 0.10 to 0.36 cm year⁻¹ with an average sedimentation rate of 0.23 cm year⁻¹. The highest (0.36 cm year⁻¹) and lowest (0.10 cm year⁻¹) sedimentation rates were observed from 9 to 20 cm and 4 to 8 cm respectively (Fig. 2). The OG core recorded a depositional history since 1850 AD with a sedimentation rate of 0.10 to 0.36 cm year⁻¹. Enhanced sedimentation of 0.36 cm year⁻¹ between 1850 and 1905 AD persisted in the region following which a declining sedimentation rate between 1905 and 2013 AD has been observed. The NKL core has recorded the depositional history since 1947 AD with a constant sedimentation rate of 0.30 to 0.32 cm year⁻¹. Opposite to the core location, the northern Kerala coast is not influenced by any major rivers, and therefore the sedimentation rate has remained almost constant with no major fluctuation during last ~65 years. As the core OKO is located opposite to Kochi, it is expected to be significantly influenced by the Periyar River. High sedimentation rates (0.69 cm year⁻¹) have been observed between 1989 and 2005 AD (16.5–5.5 cm) followed by a reduction in the sedimentation rates between 1947 and 1989 AD (30.5–16.5 cm) with a rate of 0.33 cm year⁻¹.

The ²¹⁰Pb dating indicates that the top 30–50 cm of the sediment cores collected from the coastal Arabian Sea (water depth 20–100 m) has deposited during the last 100–150 years. The sedimentation rates are different for both DWSC and SWSC. The sedimentation in off-Goa sediment cores (OG and GO) ranged between 0.23 and 0.26 cm/year, while nearly twofold increase in the average sedimentation rate is seen between central (CKT) and north (NKT) Karnataka sediment cores. Among the DWSC, sediment core from north Kerala (NKL) suggested high sedimentation rate in spite of having water depth of > 80 m.

Signatures of artificial dispersion of ¹³⁷Cs in the sediment core from the Arabian Sea

The ¹³⁷Cs dating technique has been extensively used alongside with the ²¹⁰Pb dating method for the estimation of average sedimentation rate, as the maximum ¹³⁷Cs concentration observed at any depth corresponds to the year 1963. Thus, the ¹³⁷Cs maxima act as a marker

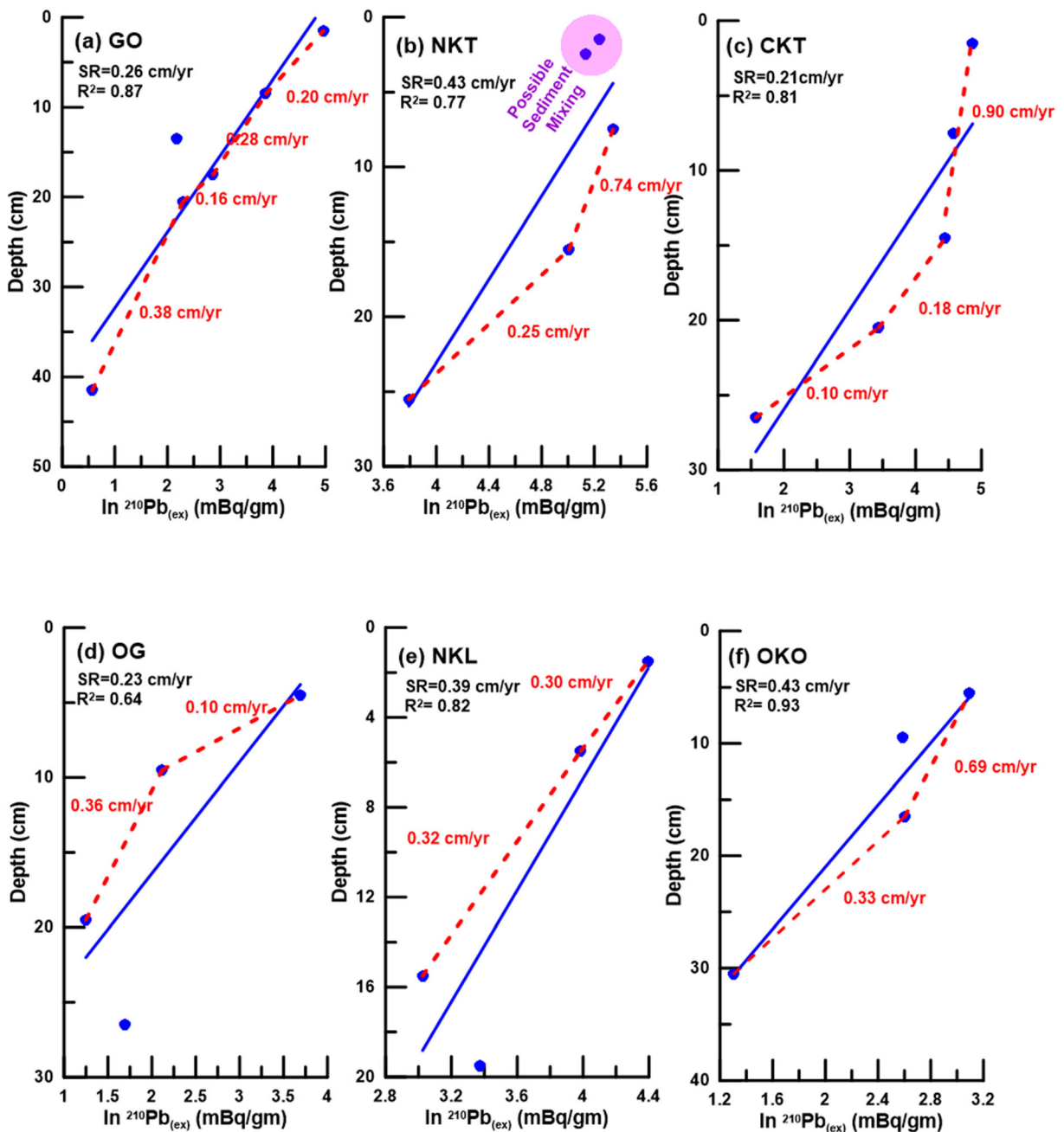


Fig. 2 Downcore profile of ²¹⁰Pb_{ex} for sediment cores from the coastal Arabian Sea. Samples highlighted and encircled represent the analysed depth but not included in the sedimentation rate estimation

of 1963 AD, when it peaked in the atmosphere primarily due to nuclear tests. However, it has been observed that anthropogenic radionuclides are generally transported down the water column via advection, diffusion or particulate scavenging process (Jha et al. 2012) and a very small fraction of the total ¹³⁷Cs has been reported

to be in a particulate phase (Hirose et al. 1992). Radionuclides transported through runoff are usually bound to particulate phase and gets deposited during sedimentation process (Jha et al. 2012); however, runoff is not a dominant source for the ¹³⁷Cs deposition (Yamagata et al. 1963). In the present study, the sedimentation rates

and year of deposition have been ascertained by $^{210}\text{Pb}_{(\text{xs})}$, which is further supported by ^{137}Cs . Some sediment cores from the coastal Arabian Sea have indicated the signatures of major events of ^{137}Cs dispersion.

Based on ^{210}Pb dating, all six sediment cores have sediment depositional history beyond 1963 (year of highest atmospheric ^{137}Cs dispersal) (Fig. 3). Since the top of any sediment core is prone to mixing and bioturbation, the ^{137}Cs peaks observed within 5 cm from the surface in the cores have not been considered. Thus, the next prominent peak of ^{137}Cs only has been used for ascertaining the sedimentation rates which is nearly 0.35, 0.51 and 0.15 cm year^{-1} respectively for GO, NKT and CKT (Fig. 3). While in other three sediment cores, sedimentation rate based on ^{137}Cs is 0.19, 0.39 and 0.61 cm year^{-1} for OG, NKL and OKO respectively.

Assuming that the study region received ^{137}Cs fallout due to Chernobyl event, the peaks at 7.5 cm and 19.5 cm in the cores NKT and OKO respectively correspond to the year 1986 (Fig. 3). In sediment core OKO, based on age-depth model interpolation, year 1986 corresponds to 18.5 cm using ^{210}Pb dating, while for ^{137}Cs , it corresponds to 19.5 cm. In all the six sediment cores, both ^{210}Pb and ^{137}Cs dating shows comparable sedimentation rates (Table 2).

Factors influencing the sedimentation rates

The sedimentation rate is extensively used to date the climatic events (Nigam et al. 1991), changes in the sediment flux (Krishnaswami and Lal 1978) and tracing the anthropogenic pollutants (Bruland et al. 1974). The coastal core (GO) located off Goa experienced low sedimentation rates between 1918 and 1936 AD (0.16 cm year^{-1}), while enhanced sedimentation rates from coastal core (GO) off Goa have been observed after 1936 AD. This is probably due to enhanced monsoonal activity and riverine flux in the region as noticed by Nigam et al. (1995) in the sediment core raised off Karwar on the western continental shelf of India. A similar observation of enhanced monsoonal activity post-1980 AD from a recent study on Goa mudflat suggests an increased sedimentation rate of 1.42 cm year^{-1} during the same period (K. T. Singh et al. 2014). Low sedimentation rates in OG compared with GO are due to waning of the terrigenous flux with increasing water depth as a function of distance from the coast (Manjunatha and Shankar 1992).

The coastal cores NKT and CKT and distant core NKL are situated along the three districts of Karnataka viz. Uttar Kannada, Udupi and Dakshina Kannada. Until 1992, slow sedimentation rate (0.25 cm year^{-1}) in the sediment core NKT has been observed followed by enhanced sedimentation rates (0.74 cm year^{-1}). A similar observation of low sedimentation rates of 0.16 cm year^{-1} until 1992 AD from mudflats of Tadri River Creek, Northern Karnataka (K. T. Singh et al. 2014), followed by an increased sedimentation rate to 2 cm year^{-1} has been noticed as a result of natural and anthropogenic processes. Abrupt decline in $^{210}\text{Pb}_{(\text{xs})}$ in the top 8 cm of the sediment core NKT resulted due to sediment mixing caused by bioturbation, core retrieval or dredging of 2012 AD in the nearby Karwar port (Naik and Kunte 2016).

Based on the studies of cores off Mangalore coast, the sedimentation rates obtained are lower (0.72 mm year^{-1} , water depth 35 m; 0.56 mm year^{-1} , water depth 45 m) than that of northern continental shelf (1.8 and 19 mm year^{-1}) due to low suspended particulate matter (SPM) contributed by Netravati and Gurupur Rivers (Manjunatha and Shankar 1992). Thus, the sediment core CKT located near Udupi district of Karnataka coast though being a coastal core has shown slowest average sedimentation rate of 0.21 cm year^{-1} , which could be attributed to low SPM. Additionally, high sedimentation rates of 0.90 cm year^{-1} at depth of 0.5–14.5 cm in the sediment core CKT could be due to local coastal erosion, as Udupi district experiences erosion along the open beaches, near rivers/estuaries mouth and the tidal reach of rivers. High erosion rate of 0.608 $\text{km}^2 \text{ year}^{-1}$ during 2000–2006 AD observed between Surathkal to Navunda along Dakshina Kannada Coast, Karnataka, by Dwarakish et al. (2008) further supports this abruptly high sedimentation rate. The sedimentation rate of 0.39 cm year^{-1} observed for the core NKL is similar to the modelled sedimentation rate (0.43–1.13 cm year^{-1} or average: 0.66 cm year^{-1}) by sediment isotope tomography (SIT) for the ^{210}Pb dated the sediment core 3112 retrieved from south of Mangalore. However, ^{210}Pb of the same core showed sedimentation rate ranged between 0.23 and 0.4 cm year^{-1} (Somayajulu et al. 1999).

Although the core location OKO is located 60 km away from the coast, it has shown nearly similar or high sedimentation rates compared with the cores retrieved from the coastal region. This is

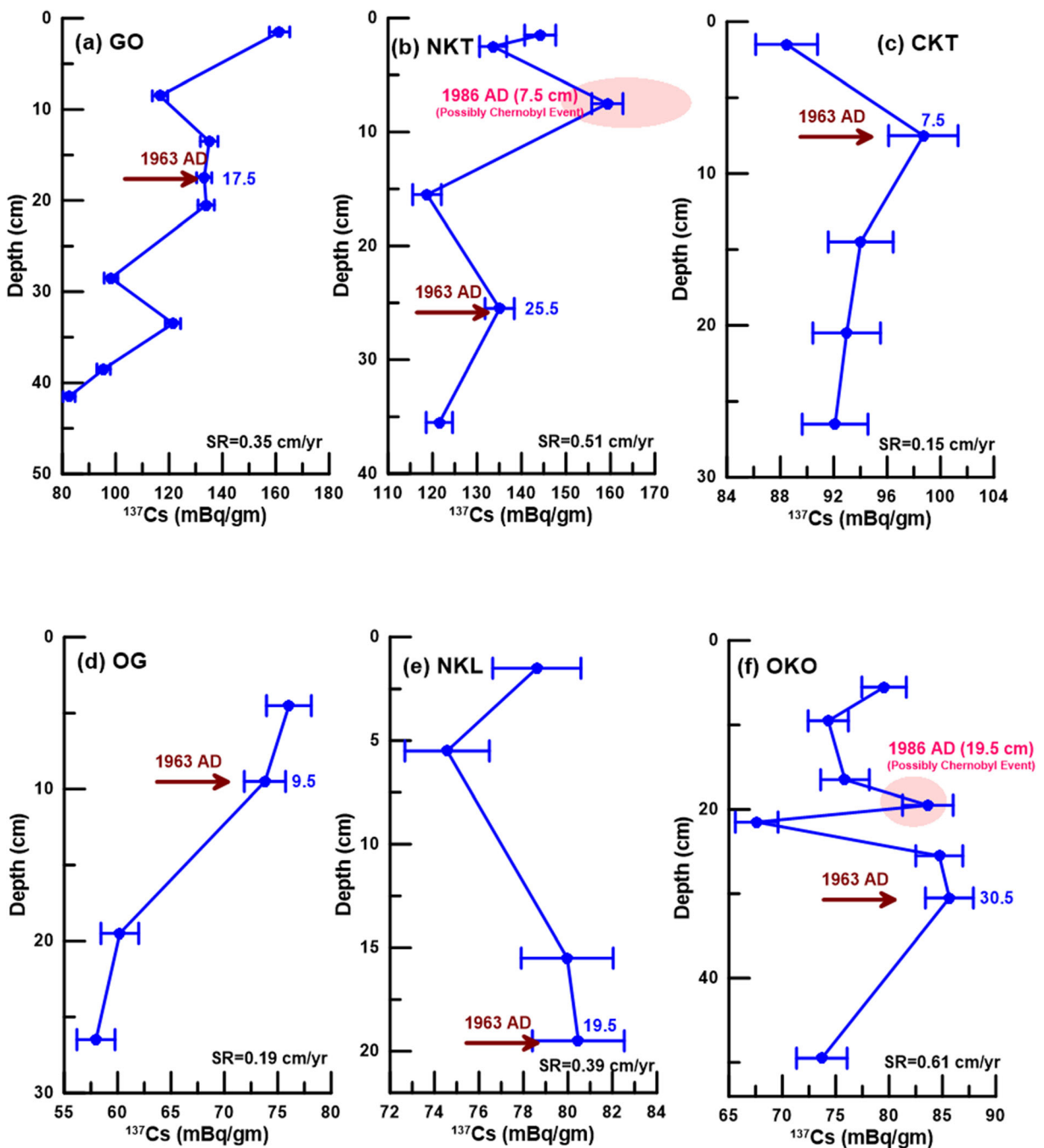


Fig. 3 Downcore variation of ^{137}Cs for the sediment cores raised during SM-29. 1963 AD and 1986 AD corresponding to nuclear test and Chernobyl accident has been marked

due to the fact that this region is influenced by the sediment deposited by the river Periyar. From the available data, the discharge of Periyar River is highest among the western flowing peninsular rivers. The sedimentation rates for the sediment core

OKO showed a gradually decreasing trend due to the construction of various dam on the river Periyar, which gradually reduced the sediment flux thereby lowering of sedimentation rates (Dwarakish et al. 2009).

Sedimentation rate and detrital flux variability

Sedimentary records from the continental margins generally provide a better understanding of past variations at high resolution because of higher sedimentation rates relative to deep ocean basins. Additionally, the continental margins directly receive detrital flux from land, and are potential sites of effective burial of carbon and detrital elements. The Indian summer monsoon (ISM) is one of the major reasons for continental flux to the coastal areas. Most rivers from the southwest coast of India are seasonal and carry maximum sediment load only during the southwest monsoon (June–September). During the southwest monsoon, the largest transport of west India coastal current is observed off the southwest coast of India. Detrital sediment is transferred from land to sea by coastal erosion and can give important information of sedimentation in coastal ocean (Hay 1998). To see the role of detrital sediment to coastal locations, Al which is a function of detrital component is plotted against year of sediment deposition (Fig. 4). As changes in detrital element flux is due to changing monsoon pattern, it can provide handful information of past deposition history in coastal oceans. Instrumental record is limited to past few hundred years only and so it is significant to go through paleo-archive proxies to understand past deposition history.

In our study along with the sedimentation rate, variability of Al was checked in two sediment cores (GO and NKT). In sediment cores GO and NKT, high sedimentation was observed until 1950 and at similar time Al concentration is also high (Fig. 4c). Detrital flux of Al decreased during 1940–1950 period, but it does not show reduction in sedimentation rate. Most importantly, in both the sediment cores, reduction in Al flux is observed at same period. In sediment cores GO and NKT, Al concentrations ranges between 3.47–7.75% and 2.33–7.44% respectively. As this region is controlled by ISM exclusively, so declining trend of Al during mentioned period is a function of ISM. When rainfall data is correlated with reduction of Al flux, it shows completely reverse trend. A study on ISM from 1944 to 2010 shows two prominent rainfall weakenings from 1854 to 1858 and also during 1920–1930 (Sontakke et al. 1993, 2008). From instrumental rainfall data, high rainfall during 1910–1915 is observed along with high flux of Al at same timings. The estimates of detrital flux to the ocean from rivers is 20×10^{12} kg year⁻¹ based on compilation of data on the

suspended sediment loads of 280 rivers discharging into the ocean (Hay 1998).

A study on speleotherms from cave of Karnataka to reconstruct paleomonsoon also shows declined rainfall during 1925 and 1941, which is in good agreement with low Al concentration and low sedimentation rate in this study (Yadava et al. 2004). While highest Al was observed during 1910 AD in GO, sediment core and same period experienced high rainfall. Similarly in NKT core, highest Al concentration was observed at 1988 and this year also had excess rainfall (Yadava et al. 2004). Both these cores are in SWSC, while other cores from DWSC show comparatively higher sedimentation rates (Fig. 4a). River discharge in the continental shelf is towards downwards and southern side sediment core receives input more from rivers which receives water mainly from ISM. Among all the sediment cores, only OG and GO provide deposition history beyond 1860 due to low sedimentation rate (Fig. 4f). All other sedimentation cores which are in southern part of the continental shelf have smaller deposition history recorded due to higher sedimentation rates.

Sedimentation rates and the annual river discharge

The primary source of sediment deposited along the coast is resultant of terrestrial weathering being transported by the river to the ocean. More than one-third of the world's river sediment load is carried by various major rivers, among which Ganga and Yellow rivers alone contribute nearly 20% of the total load (Chandramohan et al. 2001). It has been estimated that every year, $\sim 18 \times 10^{12}$ kg of suspended solids is being discharged by the global rivers to the ocean (Holeman 1968). Therefore, annual river discharge plays an important role in controlling the sedimentation rates of a particular area.

Along the coast of Goa, Mandovi and Zuari are the major rivers with discharge of 103 and 105 m³ s⁻¹ respectively (Fig. 5). The coastal core GO (average sedimentation rate of 0.26 cm year⁻¹) and the distant core OG (average sedimentation rate of 0.23 cm year⁻¹) off the Goa coast showed slow sedimentation rates compared with other cores studied in the present work, except for CKT and OKO (Fig. 2) due to low annual discharge of the Mandovi and Zuari rivers. In the case of CKT situated off Udupi, low SPM by local rivers viz. Netravati and Gurupur with an annual discharge of 240 and 40.5 m³ s⁻¹ respectively, contributes only 8% of

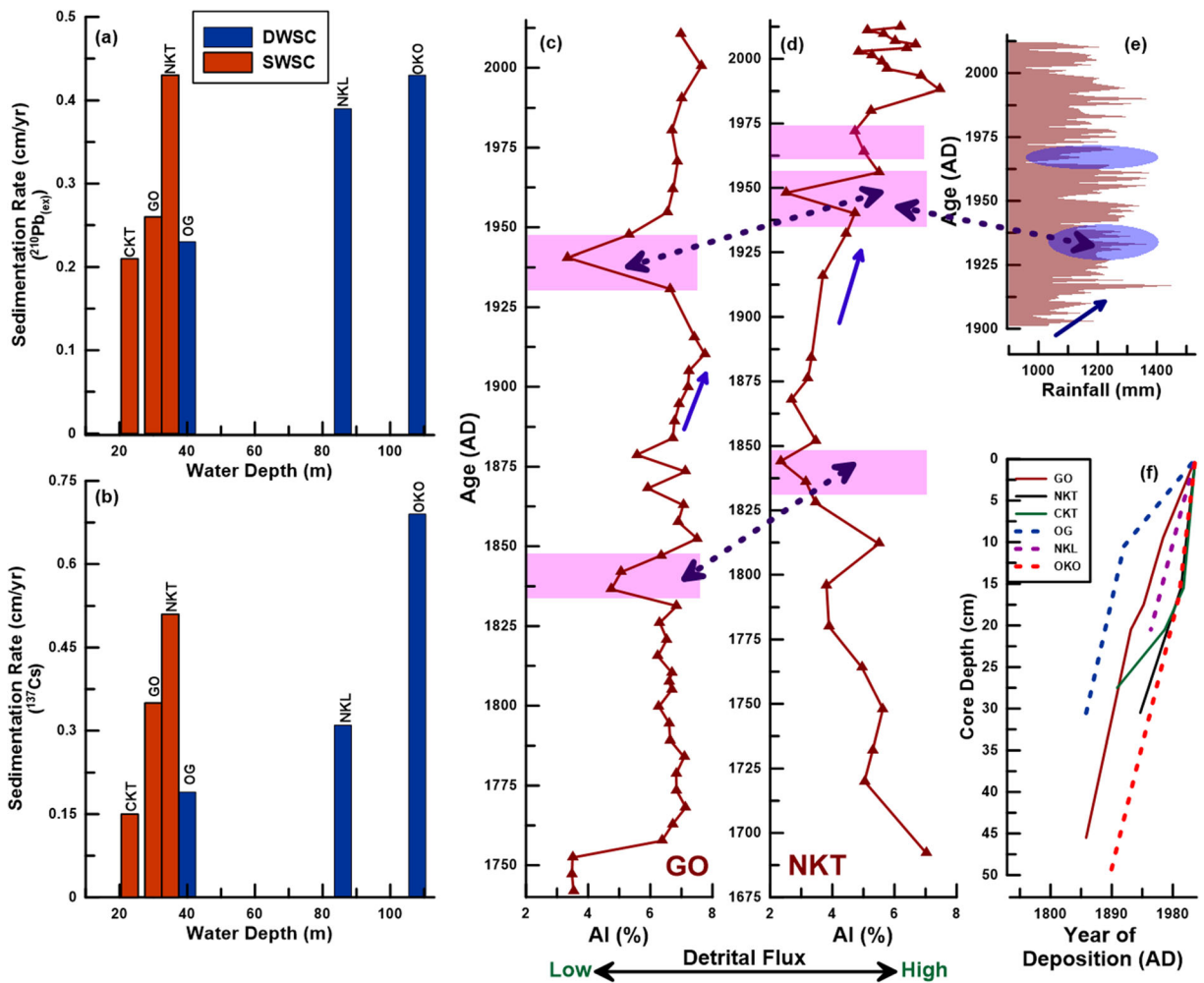


Fig. 4 Plot of sedimentation rate of all cores (a) and (b), Detrital flux of Al in cores GO and NKT (c) and (d), rainfall in the western coast of India (e) and deposition rate of sediment cores (f)

total discharge of all west-flowing rivers leading to slowest sedimentation rates (Manjunatha and Shankar 1992), despite being near coast and expected to be influenced more by terrigenous flux (Manjunatha and Shankar 1992). NKT located near Karwar is not influenced by any major river system; however, the enhanced sedimentation rate of $0.43 \text{ cm year}^{-1}$ is due to the availability of sediments due to sand and lime mining activities (K. T. Singh et al. 2014) along with the dredging activity near the Karwar Port (Naik and Kunte 2016). OKO being distant core away from the Vembanad Lake off Kerala coast has shown highest sedimentation rates among all the sediment cores from the present study. Three major rivers of Kerala are Periyar, Muvattupuzha and Chalakudy with highest annual discharge of $1364.66 \text{ cm}^3 \text{ s}^{-1}$ for Periyar River

(Fig. 5). Although the sedimentation rates has decreased with time for the sediment core OKO, the average sedimentation rates remained high in all the cores located in the northern continental shelf.

Sedimentation rates and longshore sediment transport rate

The movement of the coastal sediments by the waves and current in the littoral zone is known as littoral drift, while the rate at which the littoral drift moves parallel to the shoreline is known as longshore transport rate (Galvin 1973). A net longshore transport rate can be defined as the difference between the amounts of littoral drift transported to the right and to the left, past that point on the shoreline, in a given time period (Galvin 1973). The

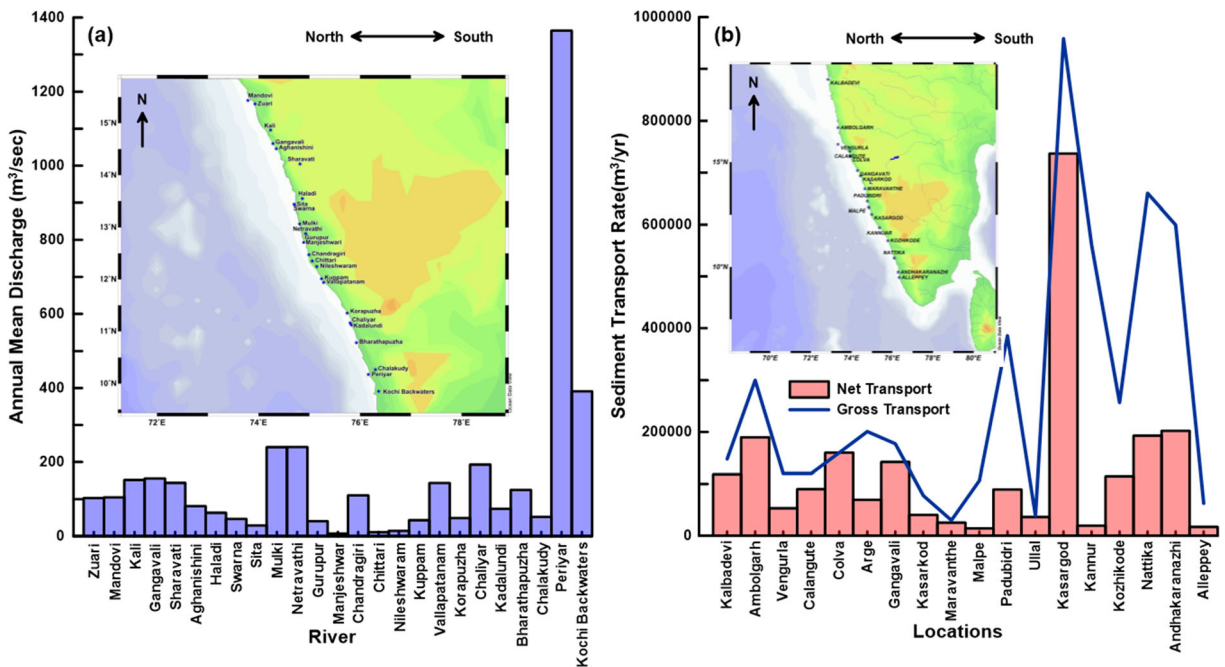


Fig. 5 Annual mean discharge of rivers, net sediment transport rate and gross sediment transport rate along the western Indian coast between Maharashtra and Kerala

littoral drift helps in deciphering the coastal erosion and accretion, which in turn helps in the development of coastal harbour and construction of coastal structures (Kunte et al. 2001). The coastal core GO being located near Calangute beach, Goa has shown average sedimentation rate of 0.26 cm year⁻¹ which is higher than CKT but lower than NKT due to the Northern drift of the littoral transport as investigated from the Calangute beach (Kunte et al. 2001). However, based on Landsat images, aerial photographs and topographic map of Goa coastal region, it was ascertained that during SW monsoon, southerly currents are eroding, while the rest of the year northerly currents resulted in accretion and hence it was inferred that although the sediment transport is bi-directional, the net major sediment transport is southwards (Kunte 1994). The study based on beach profile, monthly longshore currents, daily littoral environment and monthly beach sediment size distribution between Karwar and Bhatkal suggests an annual net transport rate towards North for Karwar and Honawar, while it is towards the south for Gokarna (Chandramohan et al. 2001). The sediment core NKT located between Karwar and Honawar coast of North Karnataka showed the highest sedimentation rates compared with all other sediment cores. The southward and northward sediment transport drifts of Gokarna and Honawar (Chandramohan et al. 2001) along with the other

natural and anthropogenic processes (K. T. Singh et al. 2014) resulted in high sedimentation rates estimated for the sediment core NKT.

The study demonstrates that highest sedimentation rate is at the core site OKO despite being situated at a distance of 60 km away from the coast with a water depth > 100 m. This sedimentation rate is comparable with the coastal core NKT situated nearly 20 km off Karnataka at a water depth of 35 m (Fig. 4). Additionally, ¹³⁷Cs-based sedimentation rate for OKO is 0.61 cm year⁻¹ which is highest among other sediment cores studied in the present work (Table 2). Therefore, the southern core site in spite of being located away from the coast, observation shows that the sedimentation rate is higher towards the southern core locations compared with northern core sites. The longshore transport of sediment along the west coast of India compiled by Kumar et al. (2006) (Fig. 5) estimated an average net sediment transport of 84,109 m³ year⁻¹ and 150,491 m³ year⁻¹ towards north and south, respectively, and suggests net sediment transport along the west coast of India is towards south (Kumar et al. 2006). Therefore, the high sedimentation rate for the core site off Kochi compared with the other core locations situated north of OKO can be attributed to the southward direction of longshore currents along the western coast

Table 3 Comparison of the sedimentation rates for the sediment cores raised from the coastal and offshore Arabian Sea both for present and earlier studies

Core ID	Latitude (N)	Longitude (E)	Water Depth (m)	Sedimentation rates (cm year ⁻¹)	Dating technique	Reference
M12	21.00	67.00	~ 2500 m	0.033	²¹⁰ Pb	Somayajulu et al. 1994
K11	16.00	69.90	~ 2500 m	0.027–0.041	²¹⁰ Pb	Somayajulu et al. 1994
2502	21.87	67.99	~ 280 m	0.1	¹⁴ C	Bhushan et al. 2001
3268G5	12.52	74.16	~ 680 m	0.008	¹⁴ C	Bhushan et al. 2001
3112G	12.00	74.95	~ 30 m	0.08–0.29	²¹⁰ Pb, ¹³⁷ Cs and ¹⁴ C	Somayajulu et al. 1999
3266G	10.33	75.59	~ 590 m	0.08–0.29	²¹⁰ Pb, ¹³⁷ Cs and ¹⁴ C	Somayajulu et al. 1999
2586	19.83	71.17	~ 52 m	0.25	²¹⁰ Pb	Dilli 1986
THC	19.04	72.98	NA	0.4–1.9	²¹⁰ Pb	Sharma et al. 1994
VC-3066	8.21	77.17	~ 21 m	0.024	¹⁴ C	Nambiar et al. 1991
VC-3126	8.24	77.16	~ 21 m	0.037	¹⁴ C	Nambiar et al. 1991
VC-3125	8.24	77.15	~ 22 m	0.012	¹⁴ C	Nambiar et al. 1991
3104G	12.80	71.70	~ 1680 m	0.0018–0.0129	¹⁴ C	Agnihotri et al. 2003
3101G	6.00	74.00	~ 2680 m	0.003–0.014	¹⁴ C	Agnihotri et al. 2003
SK-148/4	8.20	75.96	~ 1420 m	0.0045–0.009	¹⁴ C	V.P. Rao et al. 2010
MAA	15.97	73.50	NA	1.2–2	²¹⁰ Pb	K. T. Singh et al. 2014
MR	15.15	73.75	NA	1.2–2	²¹⁰ Pb	K. T. Singh et al. 2014
GH	14.53	74.35	NA	1.2–2	²¹⁰ Pb	K. T. Singh et al. 2014
GO	15.53	73.53	~ 30 m	0.16–0.38	²¹⁰ Pb	Present study
NKT	14.41	74.19	~ 35 m	0.25–0.74	²¹⁰ Pb	Present study
CKT	13.35	74.57	~ 23 m	0.10–0.90	²¹⁰ Pb	Present study
OG	15.53	73.19	~ 40 m	0.10–0.36	²¹⁰ Pb	Present study
NKL	12.38	74.48	~ 86 m	0.30–0.32	²¹⁰ Pb	Present study
OKO	10.04	75.64	~ 108 m	0.33–0.69	²¹⁰ Pb	Present study

of India. This has implications to the understanding of the sedimentation along the western coast of India which alone cannot be attributed to detrital discharge from rivers due to ISM, but also influenced by the sediment transport pattern of the region.

Conclusion

The present study attempts to provide sedimentation rates along the continental shelf from off Goa to off Kochi using various sediment cores raised during SM-29 and dated with the help of ²¹⁰Pb supported by ¹³⁷Cs. Natural and anthropogenic factors such as enhanced

monsoon, coastal erosion, riverine sediment discharge, longshore sediment transport, dam construction and dredging activity at the harbour influenced the sedimentation rates along the continental shelf between Goa and Kochi. The riverine sediment flux and longshore sediment transport played a major role in controlling the varying sedimentation rates, while other factors like dam construction and coastal erosion have influenced the local change in the sedimentations. Increased sedimentation rate from the north (off Goa) to the south (off Kochi) due to high riverine flux towards southern coast (off Kochi) has been observed with southward movement of longshore sediment transport. Detrital flux proxy and rainfall also support sedimentation rate

pattern in the region, as during low rainfall events, low Al concentrations and low sedimentation rate were observed. Similarly, during excessive rainfall event, high Al varied as a function of ISM. There is agreement between sedimentation rates estimated by both methods of ^{210}Pb and ^{137}Cs , and all six sediment cores provide sediment deposition history beyond 1963, as ^{137}Cs peak in environment could be detected in all the cores. By using ^{137}Cs as a time marker, the sedimentation rate estimated was very similar to the result of ^{210}Pb . The present study thus provides a spatial view of sedimentation rates for the continental shelf (Goa-Kochi) along the western coast of India.

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