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Some aspects on the variations in depositional flux of excess Thorium-230 in the Central Indian basin during Late Quaternary

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Abstract. Examined in this paper is the tentative history of the depositional flux of $^{230}Th_{xs}$ (the unsupported fraction of ^{230}Th scavenged from the overlying water column), for the Late Quaternary period from a sediment core of the Central Indian Basin (CIB). The measured depositional flux of $^{230}Th_{xs}$ is found substantially higher than that of the possible theoretical flux from the overlying water column. Historical records, reconstructed from the $^{230}Th_{xs}$ chronology suggests that the depositional flux has varied considerably with time, reflecting an enhanced scavenging during the Holocene and the preceding interglacial periods whereas, comparatively lower flux than the predicted one occurred during the Last Glacial Maximum (LGM) period. The average ratio of the measured depositional flux to that of the predicted flux from the overlying water column, indicates that the core site acts as a sink for $^{230}Th_{xs}$ and based on the existence of bottom current activity; the $^{230}Th_{xs}$ could be the result of focusing of younger sediments. The depositional index (Di) has also been calculated to quantify the extent of lateral supply throughout the core with time. The estimated (Di) suggests that bottom focusing and feeble deposition and/or winnowing processes had occurred and that the former was most prevalent during the Holocene and the preceding interglacials, whereas the latter was observed at the LGM period.

Keywords. ^{230}Th excess; depositional flux; bottom focusing; winnowing; interglacial; last glacial maximum.

1. Introduction

Attempts to reconstruct the past records of contemporary processes occurring in the oceanic water column were primarily based on the measurements of particle reactive daughter nuclide of U-Th series from the deep-sea sediments. These processes are known as the particle scavenging that use the historical fluxes of sedimentary component with seasonal variabilities (Rutgers van der Loeff and Berger 1991; Francois *et al* 1990; Yang *et al* 1990); the paleoproductivity (Bacon *et al* 1976; DeMaster 1981; Mangini and Diester-Hass 1983) and those associated with short term changes in the sedimentation along with climatic conditions (Broecker *et al* 1958; Bacon 1984). Among the daughter nuclide of the U-Th series, ^{230}Th, a geochemical tracer has been proven very valuable for the marine environmental studies as its source function could be easily estimated.

Particle reactive nuclide ^{230}Th ($t_{1/2} = 75{,}200$ y), is generated at a constant rate from the dissolved parent ^{234}U in the water column. Since Uranium has a long residence time, its concentration does not significantly varies in the ocean (Turekian and Chan 1971; Ku *et al* 1977). With this, it is possible to estimate theoretically the overhead production flux of ^{230}Th, scavenged by the particles settling through the water column and finally accumulating in the underlying sediment. Owing to its shorter residence time in the water column, the radioactive decay of ^{230}Th in the water column is considered insignificant (Anderson *et al* 1983). Therefore, under ideal conditions, the production flux of $^{230}\mathrm{Th}_{xs}$ from the water column should equal the depositional flux in the sediment column. Hence, by comparing the observed depositional $^{230}\mathrm{Th}_{xs}$ flux in the sediment column with the estimated flux produced from the water column may shed some light on the historical scavenging, particle rain rates (both in the present and the past) and the efficiency of bottom current reworking processes alongwith identification of winnowing of very fine particles (Shimmield *et al* 1990; Rutgers van der Loeff and Berger 1991).

The present study is an attempt to investigate (1) on the variation in the concentration and flux of $^{230}\mathrm{Th}_{xs}$ for the Late Quaternary period, (2) compare the observed inventory of $^{230}\mathrm{Th}_{xs}$ in the sediment with that of the estimated production rate from the water column and (3) to understand the role of abyssal bottom current in the depositional pattern of a sediment core from the CIB.

2. Materials and methods

Core SK 247 collected during cruise 20 of ORV Sagar Kanya retrieved from a depth of 5170 m in the radiolarian ooze facies (05°S 76°E) in the CIB was chosen for the present study. This core has earlier been studied to describe sediment type, lithology and the accumulation rate by Nath and Mudholkar (1989) and Borole (1993) respectively. Bulk density of the sediment was estimated to be of 0·49 gm cm^{-3} (Pattan and Mudholkar 1990).

In order to study the variations in the flux of $^{230}\mathrm{Th}_{xs}$ with time and to correct for the ingrowth and decay of the nuclide, we require reliable chronology which should rest on an independent assessment of age and sediment accumulation rate. In the absence of such prediction, I have chosen explicitly the $^{230}\mathrm{Th}_{xs}$ chronology (Borole 1993) based on the sediment accumulation rate of 0·43 cm ky^{-1} for fixing of a reasonable time frame for the aforementioned estimations. The identified oxygen isotope stages in the present study are tentative, which have been obtained by comparing the U/Th ages with that of the oxygen isotope stratigraphy reported by Martinson *et al* (1987).

In effect, the observed distribution of ^{230}Th might have been derived from the following main sources such as: (1) the detrital ^{230}Th deposited in equilibrium with parent ^{234}U; (2) the ingrown ^{230}Th from the authigenic ^{234}U and (3) the excess ^{230}Th scavenged from the overlying water column. Since the $^{230}\mathrm{Th}_{xs}$ considered for the present study is the one which presumably resulted from the vertical particle scavenging in the water column (with possible removal by bottom current after deposition), the measured $^{230}\mathrm{Th}_m$ has been corrected to each of these sources by equation 1 so that,

$$^{230}\mathrm{Th}_{xs} = {}^{230}\mathrm{Th}_m - ({}^{230}\mathrm{Th}_i + {}^{230}\mathrm{Th}_d) \qquad (1)$$

In order to estimate the detrital ^{230}Th, one needs to know the detrital ^{234}U. Since the authigenic uranium formed primarily in the sea water is rapidly remineralised in the deep ocean, it has been recognised that the ratio (^{238}U/^{232}Th) in surface sediments of the deep ocean shall be representative of the ^{234}U in the detrital phase (Anderson 1982). The average $^{238}U/^{232}Th$ activity ratio in the continental material for the detrital fraction of marine sediments is $0{\cdot}8 \pm 0{\cdot}2$ (Anderson *et al* 1990). I have chosen this value along with the measured ^{232}Th activity (which is assumed to be detrital in origin) to correct for the detrital ^{234}U.

$$^{234}U_d = 0{\cdot}80 \pm 0{\cdot}20 \times {}^{232}Th_m \tag{2}$$

By assuming ^{230}Th is in equilibrium with ^{234}U detrital, then

$$^{230}Th_d = 0{\cdot}80 \pm 0{\cdot}20 \times {}^{232}Th_m \tag{3}$$

The authigenic content of ^{234}U is calculated by

$$^{234}U_a = {}^{234}U_m - {}^{234}U_d \tag{4}$$

Hence the ingrowth of ^{230}Th from the authigenic ^{234}U was calculated as

$$^{230}Th_i = ({}^{234}U_m - 0{\cdot}80 \pm 0{\cdot}20 \times {}^{232}Th_m)(1 - \exp(-\lambda t)) \tag{5}$$

Substituting the appropriate values in equation (1) and then decay correcting back to the time of sediment deposition, the equation for getting the initial excess ^{230}Th at the time of sediment deposition is given by

$$\mathrm{Ao}\,{}^{230}Th_{xs} = \frac{{}^{230}Th_m - [({}^{234}U_m - 0{\cdot}80 \pm 0{\cdot}20 \times {}^{232}Th_m)1 - \exp(-\lambda t) + (0{\cdot}80 \pm 0{\cdot}20)\,{}^{230}Th_m]}{\exp(-\lambda t)} \tag{6}$$

Where subscripts '*m*', '*i*', '*d*' and '*a*' refer to measured, ingrown, detrital and authigenic concentrations (all in $\mathrm{dpm\,g^{-1}}$) respectively. λ is the decay constant of ^{230}Th ($\mathrm{ky^{-1}}$) and t is the age of the sample (ky) and $\mathrm{Ao}\,{}^{230}Th_{xs}$ is the measured initial $^{230}Th_{xs}$ activity at the time of deposition ($\mathrm{dpm\,g^{-1}}$).

The measured initial $^{230}Th_{xs}$ depositional flux through time was estimated from Cochran and Osmond (1976)

$$F_d = S\,\mathrm{Ao}\,{}^{230}Th_{xs}\,\rho \tag{7}$$

where F_d is the measured depositional flux of initial $^{230}Th_{xs}$ at time t ($\mathrm{dpm\,cm^{-2}\,ky^{-1}}$). S is the linear sedimentation rate ($\mathrm{cm\,ky^{-1}}$) and ρ is the bulk sediment density ($\mathrm{gm\,cm^{-3}}$).

For purely downward vertical transport of ^{230}Th in the water column, the theoretical production flux (F_p) of $^{230}Th_{xs}$ from the overlying 5·17 km depth is $13{\cdot}6 \pm 0{\cdot}7\,\mathrm{dpm\,cm^{-2}\,ky^{-1}}$ computed using the relation (Bacon 1984)

$$F_p = 2{\cdot}63 \times Z \tag{8}$$

Where the number 2·63 is a proportionality factor for purely vertical transport and Z is the depth of the overlying water column in km.

3. Results and discussion

3.1 ^{230}*Th excess flux*

The data are presented in table 1 and the errors quoted are due to 1σ counting statistics. Table 2 lists the calculated results for this core. The variation in the concentration of decay corrected initial excess ^{230}Th with age (corrected by equation (6) for detrital component, ingrowth from parent authigenic ^{234}U and radioactive decay) is shown in figure 1A. Figure 1B depicts the depositional flux of initial ^{230}Th$_{xs}$, estimated from equation (7) and plotted as a function of time, along with the dotted area showing the expected flux from the overlying water column. Despite the large errors, it can be clearly seen from figure 1B that the proportions of the calculated depositional flux of ^{230}Th$_{xs}$ measured are always greater than that of the water column production rate of $13{\cdot}6 \pm 0{\cdot}7$ dpm cm^{-2} ky^{-1}. This observation is suggestive

Table 1. Details of the core location, water depth together with analytical data on the measured concentration of U and Th isotopes for core SK 247 (Borole 1993).

Core: SK 247 Water depth: 5170 m Lat: 05°.0S Lon: 76°.0E

Depth (cm)	Mean depth (cm)	^{238}U (dpm g^{-1})	^{234}U (dpm g^{-1})	^{232}Th (dpm g^{-1})	^{230}Th$_m$ (dpm g^{-1})
00 – 01	0·5	0·98 ± 0·17	1·10 ± 0·18	2·39 ± 0·36	82·25 ± 4·30
01 – 02	1·5	1·31 ± 0·13	1·04 ± 0·11	3·79 ± 0·75	91·20 ± 7·35
06 – 07	6·5	1·22 ± 0·12	1·63 ± 0·14	1·69 ± 0·39	69·10 ± 5·80
08 – 09	8·5	0·74 ± 0·11	1·16 ± 0·14	2·83 ± 0·88	50·37 ± 8·80
14 – 16	15·0	1·01 ± 0·08	1·14 ± 0·09	3·51 ± 0·26	69·90 ± 3·68
21 – 23	22·0	0·97 ± 0·06	1·12 ± 0·07	2·46 ± 0·59	45·65 ± 6·04
31 – 34	32·5	1·83 ± 0·30	1·22 ± 0·09	3·05 ± 0·35	35·67 ± 2·71
36 – 38	37·0	1·27 ± 0·20	1·66 ± 0·10	**3·30 ± 0·56**	**43·80 ± 2·37**

Table 2. Calculated results for core SK 247.

Age* (ky B.P)	+ ^{230}Th$_{xs}$ (dpm g^{-1})	Ao^{230}Th$^{\#}_{xs}$ (dpm g^{-1})	Dep. Flux$ (dpm cm^{-2} ky^{-1})	Dep. Index@ (Di)
1·162	80·35 ± 4·26	81·23	17·12 ± 1·70	1·26 ± 0·14
3·488	88·23 ± 7·28	91·10	19·19 ± 1·90	1·41 ± 0·16
15·116	67·71 ± 5·78	77·81	16·39 ± 1·60	1·21 ± 0·13
19·767	48·29 ± 8·75	57·93	12·21 ± 1·20	0·90 ± 0·10
34·883	67·55 ± 3·60	93·23	19·64 ± 2·00	1·44 ± 0·16
51·163	44·00 ± 6·03	70·54	14·86 ± 1·50	1·09 ± 0·12
75·581	33·84 ± 2·65	67·94	14·32 ± 1·40	1·05 ± 0·12
86·046	41·70 ± 2·19	92·15	19·42 ± 1·90	1·43 ± 0·16

*Based on ^{230}Th$_{xs}$ chronology (Borole 1993).

+From equation (1)

#From equation (6).

$From equation (7).

@From equation (9).

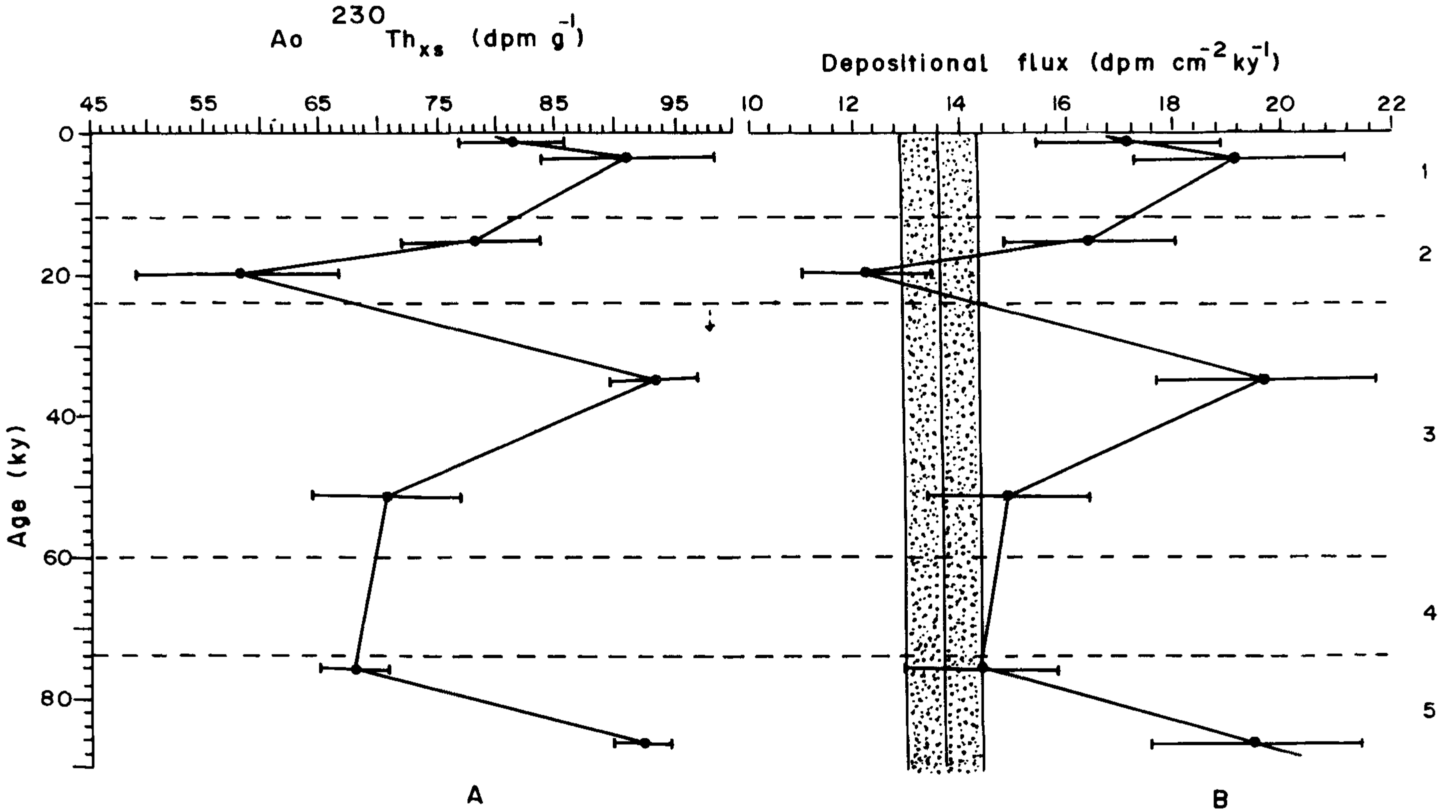

Figure 1(A). Distribution of Ao^{230}Th$_{xs}$ with time in dpm g^{-1}. The numbers 1, 2, 3, 4 and 5 are the tentative oxygen isotope stages identified by comparing the U/Th ages with the oxygen isotope stratigraphy of Martinson *et al* (1987) (**B**). Depositional flux of ^{230}Th$_{xs}$ with time. The dotted area represents the present day expected flux of 13·6 ± 0·7 dpm cm^{-2} ky^{-1}.

of the considerable variation in the depositional fluxes with time, with the highest flux recorded during the Holocene (stage 1) and middle stages (3 & 5), while lowest flux occurred at stage 2 of the oxygen isotope stage.

The average depositional fluxes ($16{\cdot}64 \pm 2{\cdot}72$) when normalized to the expected inventory ($13{\cdot}6 \pm 0{\cdot}7$) from the overlying water column, yielded an average ratio of $1{\cdot}22 \pm 0{\cdot}20$, which, within the large errors is not different from the flux expected under ideal condition ($F_d/F_p = 1$). However, when considering the alias errors involved in the computation of sedimentation rate and density with limited data, the observed ratio has got some significance, suggesting a probable supply of $^{230}Th_{xs}$ from elsewhere into the core site has eventually taken place, like for example, ^{210}Pb in the Santa Barbara basin (Krishnaswami *et al* 1975).

In effect, the plausible cause for the observed high depositional flux can be attributed to: (1) lateral transport (focusing) of sediments by abyssal bottom water, (2) presumably as a result of increased productivity in the surface waters, (3) advective scavenging of $^{230}Th_{xs}$ from the near bottom waters coupled with boundary scavenging. Although these processes seem to be reasonable to account for the observed high depositional flux, it is very difficult to reconcile the local source with the type of data presently available.

To get around this problem, we now consider the presence and northward spread of Antarctic Bottom Water (AABW) (Warren 1982; Kolla and Kidd 1982; Kolla *et al* 1976) and the lateral transport of younger sediments by its movement in this basin (Johnson and Nigrini 1982) as a plausible candidate. As such the $^{234}U/^{230}Th$ disequilibrium from the southern region of this basin suggests that surprisingly low fluxes of ^{230}Th and significant erosion (Banakar *et al* 1991) and winnowing (Borole 1993) had occurred in this basin, caused presumably by the influx of AABW current. Such a situation, if it persisted could obviously lead to the lateral transport of younger eroded/winnowed sediments (rich in $^{230}Th_{xs}$) along with the same bottom current and deposited to the places like the site of the core, under investigation. This deserves further investigation.

3.2 *Deposition index*

In order to assess the extent of bottom focusing with changes from glacial to interglacial periods, we quantify the lateral transport of $^{230}Th_{xs}$ through time by defining (Di) as:

$$(\mathrm{Di}) = F_d/F_p \tag{9}$$

As described in the introduction, in the absence of lateral transport and assuming steady state condition, the expected depositional flux should have to be balanced by the measured depositional flux so that the (Di) value be of unity. Thus, (Di) value less than unity, would indicate the net removal by erosion or by winnowing, and (Di) value higher than unity would represent net focusing processes.

The estimated (Di) values (Table 2) plotted as a function of time (figure 3) suggests that bottom focusing ($\mathrm{Di} > 1$) tends to be enhanced during the interglacial periods whereas, the observed deficiency ($\mathrm{Di} < 1$) during the LGM may be attributed to either feeble deposition or due to winnowing processes.

What must have contributed to the phenomenon of enhanced bottom focusing and winnowing during the periods of interglacial and LGM, respectively, cannot be

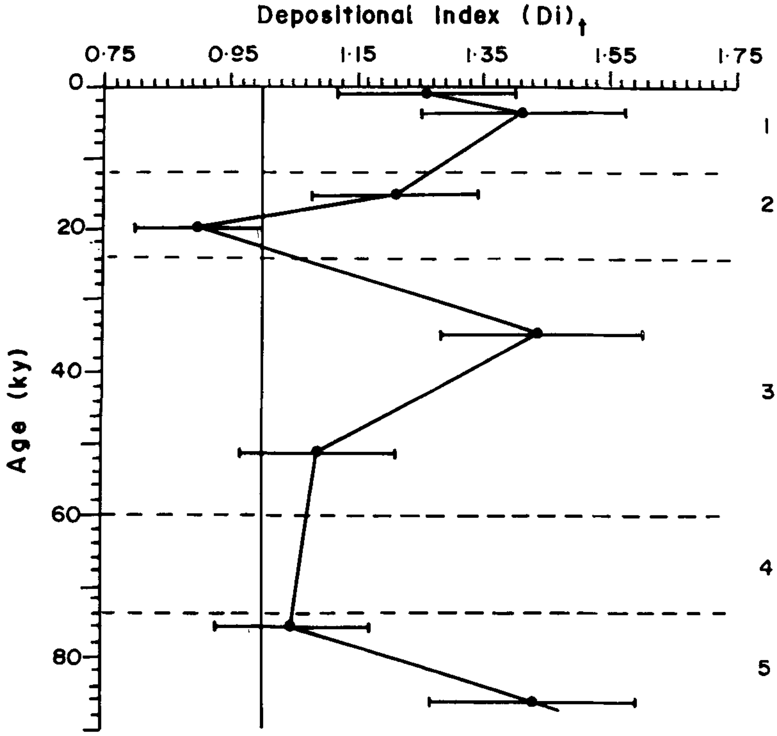

Figure 2. Age profiles of depositional index (Di). The solid line (Di = 1) shows the flux expected under steady state condition. Values < 1 indicate removal of Th while > 1 reflect supply of Th by lateral transport.

evaluated due to the high uncertainties associated with Di. However, it would be reasonable to link these processes with available paleoceanographic evidences as circumstantial. The observations of increased flux of AABW during the interglacial periods (Duplessy and Shackelton 1985; Duplessy *et al* 1984) and of the changes in the oceanic ventilation time (Kallel *et al* 1984) or surface productivity (Socci 1986) during the LGM, appear to have resulted in significant differences in the depositional fluxes of $^{230}Th_{xs}$ resulting in an enhanced bottom focusing during the interglacial periods and feeble deposition of $^{230}Th_{xs}$ and/or winnowing during the LGM.

However, interpretations of these processes remain tentative because of the incompleteness of our understanding of how the basin responds to the paleoceanographic and paleoenvironmental changes associated with glacial-interglacial cycles which needs to be investigated further. Probably a strong data base preferably with $\delta^{18}O$ studies on siliceous tests are also needed, which not only provide an independent chronology, but also the stages of the glacial/interglacial cycles at the core site.

4. Conclusions

Despite the fairly large uncertainties associated with the data, the following conclusions can be arrived at

(1) High depositional flux of $^{230}Th_{xs}$ exists with values exceeding theoretical water column production, reflecting enhanced scavenging during the Holocene and the preceding interglacials. (2) The ratio of the average measured depositional flux of $^{230}Th_{xs}$ to the predicted flux from the overlying water column, exceeds that for the flux expected under ideal condition suggesting, that the core site acts as a preferred sink for $^{230}Th_{xs}$. The observed excess flux might have been the result of focusing of younger sediments which were supplied laterally from adjacent area aided by AABW.

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