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Use of ^{210}Pb dating models for estimating sedimentation rate of a typical sediment core taken in the Ba Lat coastal area (Red River)

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Abstract: Sediment cores were taken in the coastal area of Ba Lat estuary (Red River), in the Xuan Thuy national park. Each core was cut into slices of 4 cm in thickness, numbered from top to bottom and then analyzing for radionuclides (^{226}Ra, ^{137}Cs and ^{210}Pb). Computational dating models were used to determine the age and sedimentation rate for each sediment core. This report presents the results of applying computational models to the sediment core BL13 that could provide a general methodology for determining the age and the sedimentation rate of the sediment cores taken in the coastal area of Ba Lat estuary. Results show that Constant rate of supply (CRS) model is probably the best model for determining the sedimentation rate. For the sediment core BL13, the use of the Composite model by adjusting the results of the CRS model in combination with the time marker of August 1971 (the time of the historical flood event on the Red River) seems to give the most reasonable results. The average sedimentation rate at the BL13 site before 1960 was about 0.5 cm year^{-1}. The rate had increased significantly from 1960, up to the highest value of 1.5 cm year^{-1} in the 1970s and then decreased to about 1.0 to 1.2 cm year^{-1} from the 1980s to the present. The change in the sedimentation rate could be caused by the main flow changes and large floods of the Red River from 1960 to 1980.

Keywords: *Ba Lat estuary, $^{210}Pb_{ex}$, CIC, CFCS, CRS, Composite Model.*

I. INTRODUCTION

Nuclear and isotope techniques have been used widely in research on marine environment for heavy metals, nutrient, organic substances pollution in sea sediment [1-4]. To study the history of pollutants released in marine environment, sediment samples at different depth must be taken by a core sampler. Then, sediment core should be cut into thin slices, processed, analyzed, calculated to determine the age of each slice. One of the techniques to determine the age of sediments is the ^{210}Pb technique.

The principle of the ^{210}Pb dating technique has been well documented in many scientific papers, and diverse dating models have been proposed and developed based on the $^{210}Pb_{ex}$ concentration in sediment, its flux to the sediment surface and mass accumulation rate. By applying computational models, the age of each sediment slice and sedimentation rate could be determined [5-7]. Excess ^{210}Pb technique has been recognized and widely used in assessing the rate of sedimentation in recent 100 years. History of pollution due to heavy metal and other pollutants could be restored from the sedimentation rate [8-10].

In our research project, sediment sample cores were taken in the coastal area of Ba Lat estuary (Red River). Based on the analyzed results, several computational models have been

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applied to determine the sediment age and sedimentation rate for each sediment cores.

This paper presents the application of computational models to determine the sediment age and sedimentation rate for the BL13 sediment core, and to propose a general approach for determining the sediment age and sedimentation rate of sediment cores collected in the coastal area of the Ba Lat estuary (Red River).

II. CONTENT

A. Material and method

The BL13 sediment core was taken in the flooded wetland (Figure 1) of the Xuan Thuy national park that was formed due to the agradation of the Red River in the Ba Lat estuary area [11]. The core was taken using a 5.90 cm diameter sediment corer.

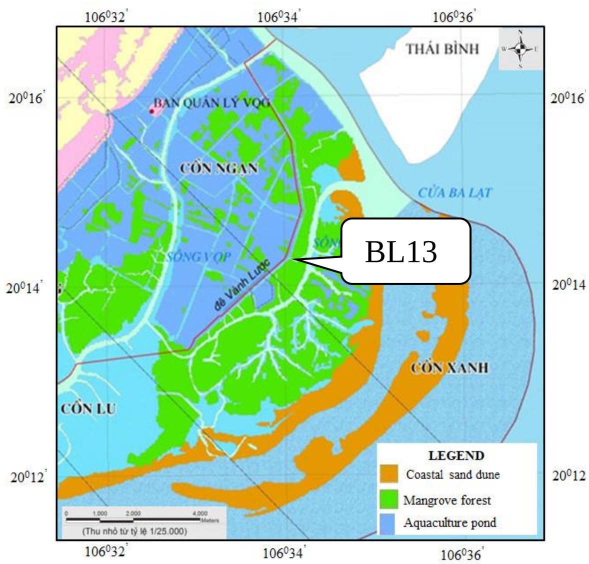

Fig. 1. The sampling location of the BL13 sediment core

Previous research articles [12-14] reported that the average sedimentation rates in Ba Lat estuary varied from 0.18 to 3.04 cm year^{-1} with an average of 0.77 cm year^{-1}. Therefore, the sediment core height was selected as 90-100 cm to cover the sedimentation period for recent 100-120 years.

Sediment cores were cut into slices of 4 cm thickness to obtain at least 20 sediment slices from each core. The sediment slices were transported to the laboratory.

In the laboratory, sample slices were air dried in ceramic bowls for further analysis. The total ^{210}Pb concentration in each sediment slice was determined by alpha spectrometry through its daughter ^{210}Po when equilibrium was guaranteed. In brief, radiochemical procedure of ^{210}Po determination includes the followings: 1 g of sediment is decomposed, then the sample is centrifuged and evaporated with 2 mol dm^{-1} HCl, ^{210}Po is then setled to deposite on a silver disc, and the prepared source is measured in an alpha spectrometer. In every analysis, the tracer ^{209}Po is used for the determination of chemical yield [15-16].

^{226}Ra (supported ^{210}Pb) concentration was determined by the gamma spectrometer CANBERRA BEGE6530. The spectrometer is calibrated using IAEA reference materials (RGU–1, RGTh–1, RGK–1 and Soil-6) to construct the detector efficiency curve. Concentration of ^{226}Ra is calculated directly from the 186.2 keV peak by separating the 186.2 keV peak of ^{226}Ra and the 185.7 keV peak of ^{235}U [17].

The excess specific activity of ^{210}Pb, or $^{210}Pb_{ex}$ ($^{210}Pb_{ex}$ = ^{210}Pb activity – ^{226}Ra activity), for each sediment slice was determined. $^{210}Pb_{ex}$ was used to calculate the age of all slices using sediment dating models. The sediment dating was performed following these steps:

a) Constructing the natural logarithmic graph of ^{210}Pb$_{ex}$ (ln(^{210}Pb$_{ex}$)) against mass accumulation depth (m_i, kg m^{-2}).

b) Use the Constant Flux Constant Sedimentation – CFCS model to determine the average sedimentation rate. This model assumes that both the $^{210}Pb_{ex}$ deposition density on the sediment surface (Bq m^{-2} year^{-1}) remain unchanged and the sedimentation mass accumulation rate r (kg m^{-2} year^{-1}) is constant.

Since the relationship between age of sediment slice and the mass accumulation depth m_i is determined from the following equation [5]:

$$t(i) = \frac{m_i}{r} \quad (1)$$

Then, if the assumptions of the CFCS model were satisfied, as the mass accumulation depth increase, the $^{210}Pb_{ex}$ of the ith slices (C_i) decrease exponentially according to the equation [5]:

$$C_i = C_0\, e^{-\lambda t(i)} = C_0\, e^{-\lambda m_i / r},$$

$$\text{or } \ln(C_i) = \ln(C_0) - \frac{\lambda}{r}\, m_i \quad (2)$$

Where:

- $t(i)$ is the duration from which the ith slice was formed (year);
- λ is the decay constant of ^{210}Pb, equal to 0.03118 year^{-1};
- C_o is the Activity of $^{210}Pb_{ex}$ in the ith sediment slice when it was formed (Bq kg^{-1});
- C_i is the $^{210}Pb_{ex}$ Activity in the ith sediment slice (Bq kg^{-1}).

The equation (2) could be solved by linear regression method. The linear regression line y = a + bx intersects with the vertical axis at $a = ln(C_0)$ and its slope is b = λ / r. Therefore $C_0 = e^a$ and r = λ/b. The C_0 and r uncertainties could be determined from the uncertainties of a and b. The age of the sediment slice *t(i)* could be determined from the equation (1).

The CFCS model is applicable if the graph showing the relationship between $ln(C_i)$ and m_i has linear form. If the graph has segmented linear form (more than 2 linear segments with different slope), the average r could be determined for each of segment and C_0 could be determined from the r value of the previous linear segment.

c) Use the CFCS model to determine the initial $^{210}Pb_{ex}$ activity C_0 for the uppermost linear segment. This C_0 value would be used by the Constant Initial Concentration (CIC) model to estimate the age of all sediment slices. The age of the ith sediment slice was calculated by the following equation [5]:

$$t(i) = \frac{1}{\lambda}\, ln \frac{C_o}{C_i} \quad (3)$$

d) Use the CFCS model on the bottom slices of the sediment core to determine the total inventory A(j) of $^{210}Pb_{ex}$ under the jth sediment layer. Suppose that the average r could be determined by CFCS, at least for the deepest layers of the sediment core, the inventory of $^{210}Pb_{ex}$ under the jth sediment layer could be calculated from the following equation [5]:

$$A(j) = \frac{r.C(j)}{\lambda} \quad (4)$$

Therefore, the total inventory of the sediment core A(0) could be calculated as follows [5]:

$$A(0) = \delta A + A(j) \quad (5)$$

Where: δ(A) is the total inventory from the surface to the deepest slice of the sediment core.

From the determined A(0), the age of all sediment slices could be determined using the Constant rate of supply model (CRS) model. This model is based on the assumptions that the $^{210}Pb_{ex}$ deposition density on the sediment surface (Bq m^{-2} year^{-1}) remain unchanged with time while the mass accumulation rate r (kg m^{-2} year^{-1}) could change. The age of the ith sediment slice is given by the following equation [5]:

$$t(i) = \frac{1}{\lambda} \ln \frac{A(0)}{A(i)} \quad (6)$$

Where:

- $A(0)$ is the total inventory of the sediment core (Bq m^{-2});

- $A(i)$ is the total inventory below the i^th^ sediment slice (Bq m^{-2}).

e) The sedimentation mass accumulation rate of the ith sediment slice (r_i, kg m^{-2} year^{-1}) could be calculated from the age of the sediment slice by the following equation [5]:

$$r_i = \frac{\lambda A(i)}{C(i)} = \frac{\Delta m(i)}{\Delta t(i)} \quad (7)$$

And the sedimentation rate of the ith sediment slice (s, m year^{-1}) could be determined by the following equation [5]:

$$s_i = \frac{\Delta z(i)}{\Delta t(i)} \quad (8)$$

Where:

- $\Delta m(i)$ is the mass of the sediment slice (kg m^{-2});
- $\Delta z(i)$ is the thickness of the sediment slice (m);
- $\Delta t(i)$ is the duration the sediment slice was formed (year), calculated from the age of the sediment slice.

f) If the two reference time markers are known and the $^{210}Pb_{ex}$ dating results show large discrepancy with the time markers, the Composite model (CM-CRS) could be used to determine the change in the $^{210}Pb_{ex}$ deposition density with time, as mentioned in [6].

The discrepancy between the age determined by the CRS model and the time markers could reflect the change in the rate of $^{210}Pb_{ex}$ supply at the sediment core sampling location. The discrepancy could be attributed to events such as: flood, sediment subsidence, whirlpool, change in land use.

Let x_1 and x_2 be the depths of two sediment slices with known ages of t_1 and t_2, respectively, the average $^{210}Pb_{ex}$ deposition density is calculated by the formula [6]:

$$P = \frac{\lambda \boldsymbol{\Delta} A}{e^{-\lambda t_1} - e^{-\lambda t_2}} \quad (9)$$

Where $\boldsymbol{\Delta} A$ is the discrepancy in $^{210}Pb_{ex}$ inventory between x_1 and x_2. By assuming the inventory during this sedimentation period remain unchanged, the calibrated sediment age and sedimentation rate could be determined using the principles of the CRS model for the $^{210}Pb_{ex}$ inventory. From the equations of the CRS model and the calculated P, the age of the sediment layer at the depth of x ($x_1 < x < x_2$) could be calculated from the formula [6]:

$$\frac{P}{\lambda} e^{-\lambda t} = \frac{P}{\lambda} e^{-\lambda t_1} + \Delta A(x_1, x) \quad (10)$$

Where $\Delta A(x_1, x)$ is the $^{210}Pb_{ex}$ inventory discrepancy between x_1 and x. Since time markers t_1 and t_2 have assigned in the equation (10), the ages determined for the sediment layers between x_1 and x_2 do not have large uncertianty even when the rate of $^{210}Pb_{ex}$ supply varies.

B. Results

The graph in Figures 2 shows the relationship between $^{210}Pb_{ex}$ activities versus the depth of the sediment core. It could be seen that the $^{210}Pb_{ex}$ activity decrease gradually from the surface to the depth of 54 cm, before fluctuating arbitrarily, reaching the background level (approximate to the $^{210}Pb_{ex}$ measuring uncertainty) at the depth of 90 – 94 cm.

Figure 3 shows the natural logarithm fluctuation of excess ^{210}Pb activity (ln($^{210}Pb_{ex}$)) versus mass accumulation depth and the calculation results of the CFCS model for the BL13 core. The graph has two linear segments with different slopes, corresponding to two sedimentation period of different sedimentation rates. The upper linear segment (from the surface to the depth of 58 cm, m_i = 65.66 g cm^{-2}) gives a C_0 value of 37.88 Bq kg^{-1} and an average mass accumulation rate of 1.34 g cm^{-2} year^{-1}. The lower linear segment gives an average mass accumulation rate of 0.78 g cm^{-2} year^{-1}, nearly half of that in the upper segment. Table I shows sediment dating results of all sediment slices using equation (1). The found C_0 value of 37.88 Bq kg^{-1} was used in the CIC model for dating of all sediment slices by the equation (3). The calculation results are shown in Table I.

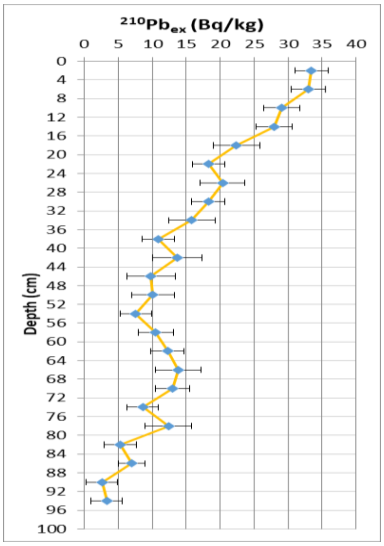

Fig. 2. The relationship between $^{210}Pb_{ex}$ activities vs the core depth

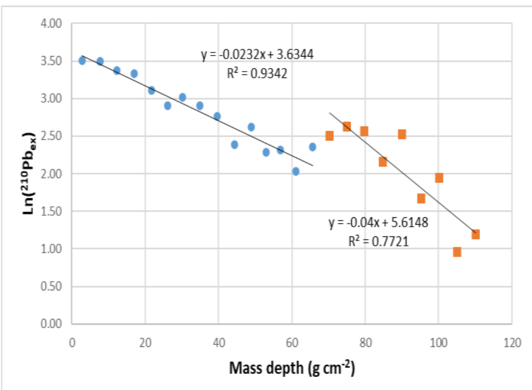

Fig. 3. The fluctuation of $\ln(^{210}Pb_{ex})$ with the mass accumulation depth and the calculated results from CFCS models fo the BL13 sediment core

For the lower linear segment (Figure 3), the calculated using equation (4) inventory of $^{210}Pb_{ex}$ (below the 24^{th} sediment layer) was found to be 372 Bq m^{-2} and the total inventory of the sediment cores A(0) was found to be 17220 Bq m^{-2}. Applying equation (6), the calculated ages of all sediment slices are shown in Table I.

In addition, the CM-CRS model have been tested to adjust the results of the CRS models for different known time markers. For the BL13 sediment core, the peak of highest sedimentation rate from the CRS model (Figure 4), corresponds to August 1971 when the historic flood occurred in the Red River [15], which might bring about the increase in the sediment supply to the Ba Lat estuary.

Applying the equation (10), the ages of all sediment slices of the BL13 sediment core were calcuted by CM-CRS model, as shown in Table I. From the age dating of sediment slices using the CRS model, the sedimentation rates of these slices had been calculated by the equation (8), as shown in Figure 4. The age dating of sediment slices using the CM-CRS model (August 1971) was also used for calculating the sedimentation rates of all sediment slices by the equation (8), as shown in Figure 5.

C. Discussion

Figure 6 summarizes the calculation results of different age dating models for the BL13 sediment core. From Figure 6, the following comment could be made:

- Results of the CIC model were inconsistent with the assumption of the model that the sediment core was undisturbed and thus, deeper sediment slices would be older. However, if a sediment slice has higher $^{210}Pb_{ex}$ activity (compared to the upper sediment slice), according to Equation (3), the slice would be younger. The CIC model is only valid when the $^{210}Pb_{ex}$ activity decreases gradually with depth.

- The CFCS model could be used to determine the average sedimentation rate for a constant sedimentation period. Results of the CFCS model applied to BL13 core were pretty good (R^2 = 0.9324) for the upper linear segment (from the surface to the depth of 58 cm) with an average sedimentation rate of 1.34 g cm^{-2} $year^{-1}$. However, the results for the lower linear segment were not quite reliable, especially when the sedimentation process has many periods and so the transitiosn points are difficult to find.

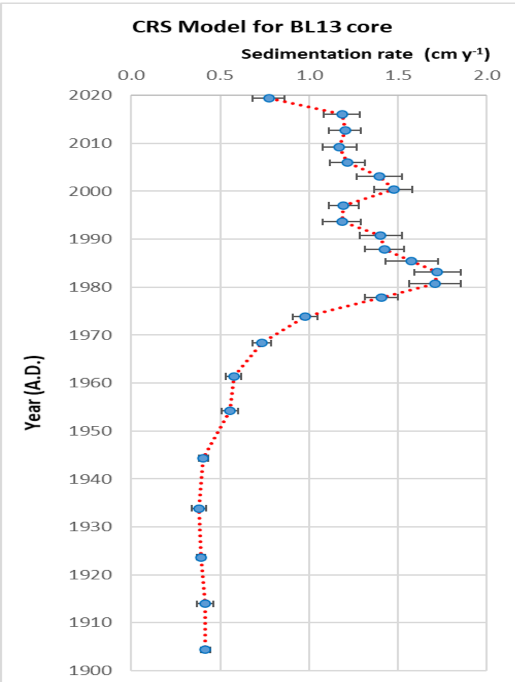

Fig. 4. The sedimentation rate variation with time from the CRS calculation results

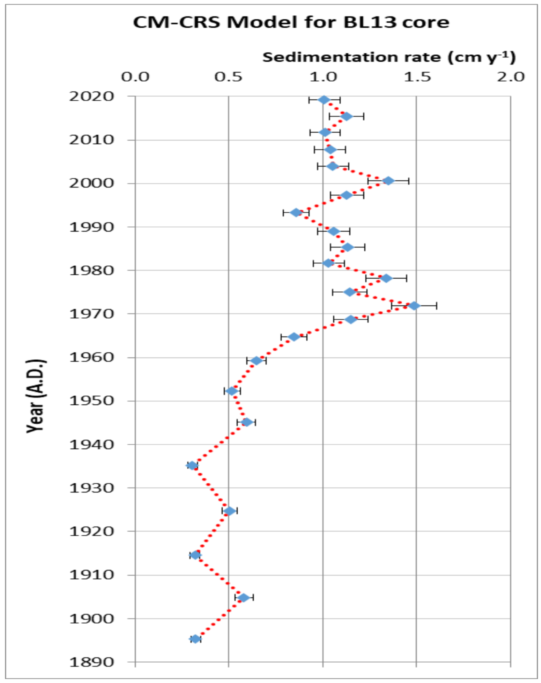

Fig. 5. The sedimentation rate variation with time from the CM-CRS (August 1971) model calculation results

- Results of the CRS and CFCS models show similar average sedimentation rate. In addition, CRS model could also calculate the sedimentation rates of all sediment slices. Thus, CRS model could be the best model to use to find the change of the sedimention rates with time.

- Results of using the CM-CRS to adjust the result of the CRS model (based on the assumption that the highest sedimentation rate by CRS model corresponds to the time of August 1971) are consistent with that of CFCS model for the upper linear segment. It could be judged that this CM-CRS model is the most suitable model for the dating of the BL13 sediment core.

Figures 4 and 5 indicate that the sedimentation rate in the period of 1960 to present has increased considerably. The average sedimentation rate before 1960 was 0.5 cm years^{-1}, has increased gradually before reaching the highest value of 1.5 cm years^{-1} in 1970s. Then, the rate has decreased to the range of 1.0 - 1,2 cm years^{-1} from 1980s to present. The fluctuation of the sedimentation rate with time could be explained as follow:

- The Red River has a large amount of total suspensed solid (TSS) in the water, especially in the rainy season (from April to October). Since 1960, an irrgation dam was build at Ngo Dong, in So river (a tributary of the Red River) [11]. Perhaps, during flood season, the dam gate in So river is closed for protection against the flood, most of TSS from the Red River goes to Ba Lat estuary. That could be the reason of increasing the sediment supply and sedimentation rate in the Ba Lat estuary since 1960.

- Before 1971, the Ba Lat estuary was located about 10 km to the north of the current location. After the historic flood in August 1971, the Ba Lat estuary moved south to the current location. The Kate storm in 1973 pushed sand dunes, blocking the main river stream, forming the present Ba Lat estuary [14]. Perhaps, flood and the change in the river's flow have brough about the constant fluctuation of the sedimentation rate in Ba Lat estuary, especially in the 1970s.

- Since 1980, the sedimentation rate has decreased to 1.0 – 1.2 cm years^{-1}. The decrease could be attributed to the construction of Hoa Binh hydraulic dam in Da River (1979 – 1994), affecting the amount of TSS poured to the Ba Lat estuary. In Son Tay, the amount of TSS poured to the Red river have decreased by about 50% since the Hoa Binh hydraulic plant began its operation [14].

Table I. Age dating (A.D.) calculation results of all sediment slices from the BL13 sediment core using different models

No	Depth (cm)	CIC	CFCS	CRS	CM-CRS (August 1971)
1	2	2016.7	2019.1	2019.4	2019.2
2	6	2016.3	2015.5	2016.0	2015.4
3	10	2012.2	2012.0	2012.6	2011.7
4	14	2010.9	2008.5	2009.2	2007.8
5	18	2003.9	2005.0	2005.9	2004.0
6	22	1997.4	2001.7	2003.1	2000.6
7	26	2000.8	1998.6	2000.3	1997.3
8	30	1997.4	1995.2	1997.0	1993.2
9	34	1992.7	1991.7	1993.6	1989.0
10	38	1980.8	1988.1	1990.8	1985.4
11	42	1988.1	1984.7	1987.9	1981.7
12	46	1977.3	1981.7	1985.4	1978.2
13	50	1978.3	1978.8	1983.1	1975.0
14	54	1969.2	1975.7	1980.7	1971.9
15	58	1979.6	1972.3	1977.9	1968.8
16	62	1984.5	1966.2	1973.8	1964.7
17	66	1988.4	1960.3	1968.4	1959.3
18	70	1986.5	1953.9	1961.4	1952.3
19	74	1973.2	1947.3	1954.2	1945.1
20	78	1985.0	1940.7	1944.3	1935.2
21	82	1957.8	1933.9	1933.9	1924.8
22	86	1966.4	1928.0	1923.6	1914.6
23	90	1934.8	1921.6	1914.0	1904.9
24	94	1942.4	1914.7	1904.3	1895.3

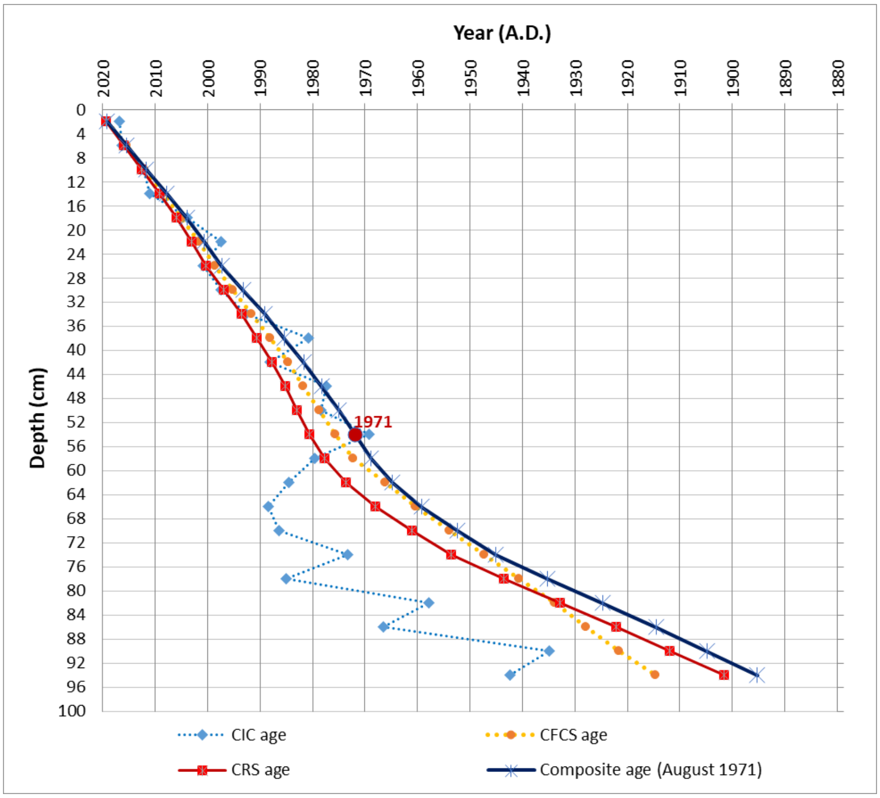

Fig. 6. Age calculation results from various models for the BL13 sediment core

III. CONCLUSIONS

In most of the cases, the CIC model should not be used for areas where the sedimentation rate change constantly such as Ba Lat estuary. The CFCS model could be used to estimate the average sedimentation rate and the total inventory of the sediment core. The CRS is probably the best model for determining the sedimentation rate in the Ba Lat estuary. For the BL13 sediment core, the use of the CM-CRS by modifying the results of the CRS model in combination with the time of August 1971 (when a historic flood occurs in the Red River) gave the most suitable results.

The average sedimentation rate at the BL13 location before 1960 was 0.5 cm $years^{-1}$, from 1960 to present, the rate has increased considerably, reached a peak at 1.5 cm $years^{-1}$ in 1970s, before decreasing to 1.0 – 1.2 cm $years^{-1}$ from 1980s to present. The fluctuation of the sedimentation rate could be attributed to the change in main river flows and major floods occured in the Red River from 1960 to 1980.

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REFERENCES

[1]. Meng W., Qin Y., Zheng B., Zhang L. "Heavy metal pollution in Tianjin Bohai Bay, China", *Journal of Environmental Sciencies*, 20, 814-819, 2008.

[2]. Nobi E.P., Dilipan E., Thangaradjou T., Sivakumar K., Kannan L. "Geochemical and geo-statistical assessment of heavy metal concentration in the sediments of different coastal ecosystem of Andaman Islands, India", *Estuarin, Coastal and Shelf Science*, 87, 253-264, 2010.

[3]. Buccolieri A., Buccolieri G., Cardellicchia N. "Heavy metals in marine sediments of Taranto Gulf (Ionian Sea, Southern Italy)", *Marine Chemistry*, 99, 227-235, 2006.

[4]. Farmer J.G. "Metal Pollution in Marine Sediment Cores from the West Coast of Scotland", *Marine Environmental Research*, 8, 1-28, 1983.

[5]. Sanchez-Cabeza J.A., Ruiz-Fernandez A.C. "^{210}Pb sediment radiochronology: An integrated formulation and classification of dating models", *Geochimica et Cosmochimica Acta*, 82, 183–200, 2012.

[6]. Appleby P. G. "Chronostratigraphic techniques in recent sediments", *In: Tracking Environmental Change Using Lake Sediments, vol. 1 (eds. W. M. Last and J. P. Smol), 171– 201*. Basin Analysis, Coring and Chronological Techniques. Kluwer Academic Publishers, Dordrecht, The Netherlands, 2001.

[7]. Ligeroa R.A., Barreraa M., Casas-Ruiza M., Salesb D., López-Aguayoc F., "Dating of marine sediments and time evolution of heavy metal concentrations in the Bay of Ca´diz, Spain", *Environmental Pollution*, 118, 97-108, 2002.

[8]. Fukue M., Nakamura T., Kato Y., Yamasaki S. "Degree of pollution for marine sediments", *Engineering Geology*, 53, 131-137, 1999.

[9]. Zourarah B., Maanan M., Carruesco C., Aajjane A., Mehdi K., Freitas M.C. "Fifty-year sedimentary record of heavy metal pollution in the lagoon of Oualidia (Moroccan Atlantic coast)", *Eustuarine, Coastal and Shelf Science*, 72, 359-369, 2007.

[10]. Mil-Homens M., Stevens R.L., Boer W., Abrantes F., Cato I. "Pollution history of heavy metals on the Portuguese shelf using ^{210}Pb-geochronology", *Science of the Total Environment*, 367, 466-480, 2006.

[11]. Tran Thi Thanh Nhan, Tran Nghi, Tran Ngoc Dien, Dinh Xuan Thanh, Tran Thi Dung, Nguyen Thi Phuong Thao, Dinh Xuan Truong, Do Manh Tuan, Doan Dinh Lam. "The Holocene - Present Shoreline Migration off Thai Binh – Nam Dinh in Relation to Evolution of Deltaic Lobes and History of the So River", *VNU Journal of Science: Earth and Environmental Sciences*, 34 (4), 2018. Available at: <https://js.vnu.edu.vn/EES/article/view/4346>.

[12]. Nhon Dang Hoai, Thanh Tran Duc, Huy Dinh Van, Hai Phan Son, Ha Nguyen Manh, Lan Tran Dinh, Duan Xiaoyong, Ve Nguyen Dac "Sedimentation Rates and Heavy Metal Concentrations in the Tidal Flats of North Vietnam", *Pol. J. Environ. Stud.*, 28 (5), 3721-3733, 2019.

[13]. Van Santen P., Augustinus P.G.E.F., Janssen-Stelder B.M., Quartel S., Tri N.H. "Sedimentation in an estuarine mangrove system", *Journal of Asian Earth Sciences*, 29, 566–575, 2007.

[14]. van den Bergh G.D., Boer W., Schaapveld M.A.S., Duc D.M., van Weering, Tj.C.E. "Recent sedimentation and sediment accumulation rates of the Ba Lat prodelta (Red River, Vietnam)", *Journal of Asian Earth Sciences*, 29, 545–557, 2007.

[15]. Martin P. & Hancock G. "Routine analysis of naturally occurring radionuclides in environmental samples by alpha-particle spectrometry", *Research Report 7*, Supervising Scientist for the Alligator Rivers Region, 1992.

[16]. Szarlowicz, K. "Optimization of the radiochemical procedure of 210Po determination in small amounts of sediment samples", *Int. J. Environ. Sci. Technol.*, 16, 5735–5740, 2019.

[17]. De Corte F., Umans H., Vandenberghe D., De Wispelaere A., Van den haute P. "Direct gamma-spectrometric measurement of the ^{226}Ra 186.2keV line for detecting ^{238}U/^{226}Ra disequilibrium in determining the environmental dose rate for the luminescence dating of sediments", *Appl. Radiat. Isot.*, 63(5), 589–598, 2005.