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# Chernobyl still with us: $^{137}$Caesium activity contents in seabed sediments from the Gulf of Bothnia, northern Baltic Sea

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A B S T R A C T

Anthropogenic radionuclides are among those human impacts, which can be seen widely in the marine and terrestrial ecosystems. Fallout from the 1986 Chernobyl nuclear power plant accident has rendered the Baltic Sea as the most polluted marine body in the world with respect to $^{137}$Cs.

This research investigated sediment cores from 56 sites around the Gulf of Bothnia, Baltic Sea. Radioactivity from $^{137}$Cs in sediments has generally declined due to natural/radioactive decay of $^{137}$Cs over the last decades. However, $^{137}$Cs contents in subsurface sediments remain at elevated levels compared to pre-Chernobyl levels.

The highest $^{137}$Cs activity contents in subsurface sediments (>4000 Bg kg$^{-1}$) occur in coastal areas including estuaries. These areas often experience severe anthropogenic pressure. The southern Bothnian Sea, Kvarken archipelago, and southern Bothnian Bay all show elevated $^{137}$Cs values in subsurface sediments.

Sedimentary $^{137}$Cs can also help constrain recent rates of sedimentation. Post-Chernobyl sedimentation rates in the Gulf of Bothnia varied from 0.1 to 4.8 cm/year with an average sedimentation rate of 0.54 cm/year.

## 1. Introduction

Over the past century, increased anthropogenic activity has altered both marine and terrestrial environments worldwide. Anthropogenic radioactive substances or radionuclides produced by atmospheric nuclear weapons tests, nuclear power plant accidents, nuclear fuel processing plants, radioactive waste dumping, and general nuclear power plant activity can get dispersed in ecosystems, biota, and even in the sedimentary record (Nielsen et al., 2010).

The Chernobyl nuclear power plant accident occurred on Saturday, April 26, 1986, in Chernobyl, Ukraine (former USSR). Radioactive fallout after the power plant explosion spread throughout Europe. The Baltic Sea (Fig. 1) was the marine area most affected by the fallout. The initial radioactive clouds from Chernobyl travelled north to deposit in the Baltic Sea and its drainage area (Povinec et al., 1996; HELCOM, 2003, 2007; Ilus, 2007).

Radioactive fallout consists of various anthropogenic radionuclides. Caesium-137 ($^{137}$Cs) and caesium-134 ($^{134}$Cs) were the most abundant radionuclides within Chernobyl fallout. Baltic Sea sediments also show elevated levels of ruthenium-103 ($^{103}$Ru), ruthenium-106 ($^{106}$Ru), silver-110m ($^{110m}$Ag), and antimony-125 ($^{125}$Sb) from the Chernobyl accident (HELCOM, 2003, 2007).

Here we focus on $^{137}$Cs because it was the main long-lived radionuclide in Chernobyl fallout. With a half-life of ca 30.05 years, the isotope remains at elevated levels in the environment over historical time frames.

The Baltic Sea is the most polluted sea region in the world with respect to $^{137}$Cs (IAEA, 2005; HELCOM, 2018a). Pollution primarily represents radioactive fallout from the Chernobyl accident. This event released a total $^{137}$Cs input of 4700 TBq into the Baltic Sea region (Nielsen et al., 1999). This amount gives 2015 decay corrected estimates of 2700 TBq (HELCOM, 2018a). Runoff and fluvial transport of Chernobyl-derived $^{137}$Cs into the Baltic Sea is estimated to be 300 TBq or 6–7% of the total fallout load delivered to the environment (Ilus and Ilus, 2000; HELCOM, 2003). The decay corrected total river $^{137}$Cs input to the Baltic Sea by 2015 was estimated at 200 TBq (HELCOM, 2018a). The second most important source of $^{137}$Cs to the Baltic Sea is global fallout from atmospheric nuclear weapon tests carried out mainly during the late 1950s and early 1960s. In relative terms, Chernobyl fallout represents about 79% and nuclear weapons test fallout about 16% of $^{137}$Cs input to the Baltic Sea (HELCOM, 2003, 2009, 2018a; Nielsen et al., 2010). In the central Baltic Sea sediments, reported $^{137}$Cs activity

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contents derived originally from nuclear weapons tests are ca. 50 Bq $kg^{-1}$ (e.g. Moros et al., 2017).

$^{137}Cs$ from the Chernobyl event fell unevenly throughout catchment area of the Baltic Sea and further shows an uneven distribution in seafloor environments (Fig. 2). However, distribution of marine deposition has not been modelled in such detail. The greatest deposition occurred in areas surrounding the Gulf of Bothnia and the Gulf of Finland (Fig. 2) (HELCOM, 1995, 2007). The highest $^{137}Cs$ activity contents and total amount (per square meter) in bottom sediments appear in northerly areas of the Bothnian Sea, southerly areas of the Bothnian Bay, and easterly areas of the Gulf of Finland (HELCOM, 2003, 2007, 2009, 2013; Ilus, 2007).

$^{137}Cs$ activity contents have been measured and monitored around the Baltic Sea since the early 1960's (Herrman, 2000). Measurements

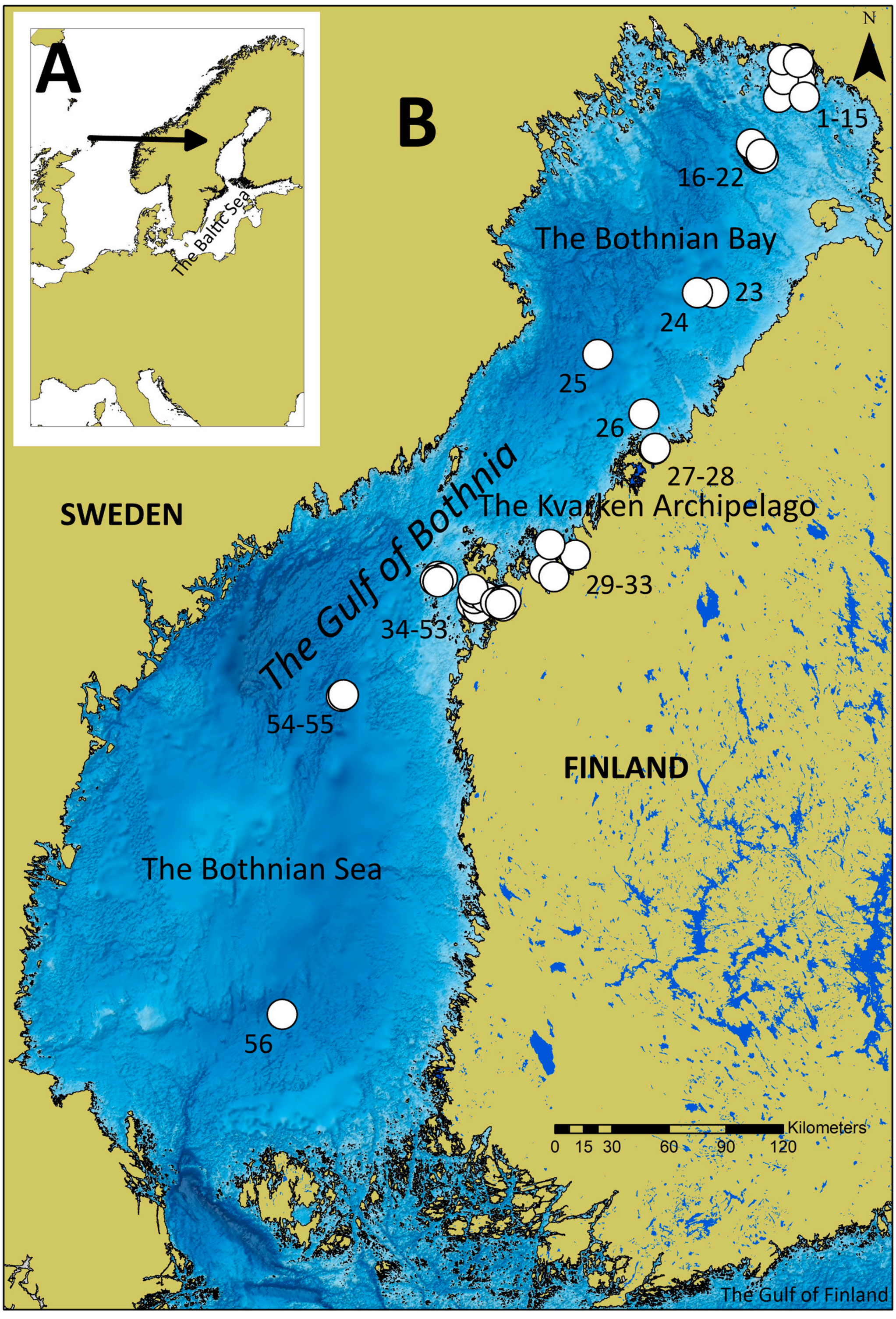


**Fig. 1.** A. Location of the study area, the Bothnian Sea, including the Kvarken archipelago and the Bothnian Bay in the Gulf of Bothnia, northern Baltic Sea. B. Bathymetric map of the Gulf of Bothnia area. White dots and numbers (1–56) show the locations of sampling sites. Bathymetric data: HELCOM, BSHC (Baltic Sea Bathymetry).

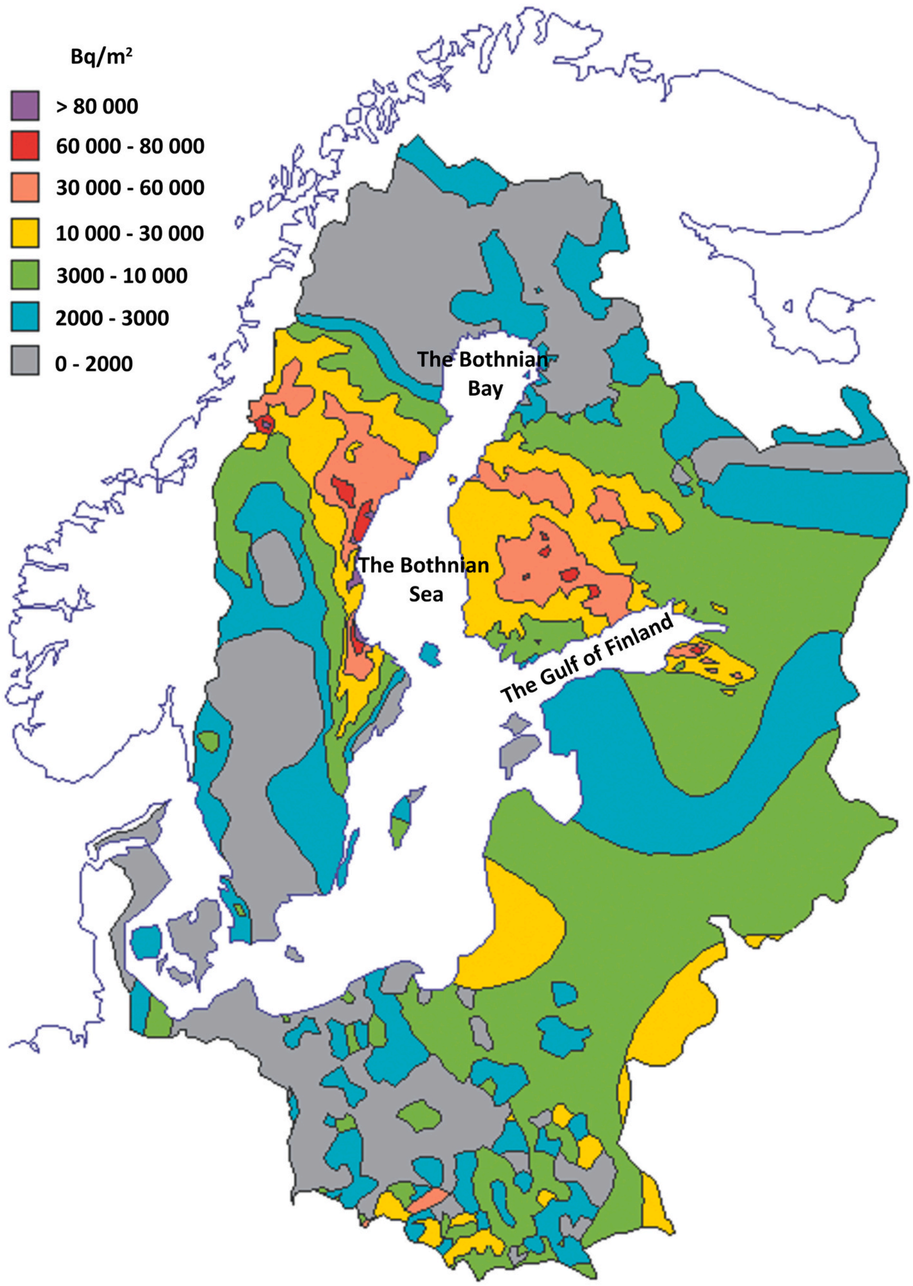


**Fig. 2.** Terrestrial deposition of Chernobyl-derived $^{137}Cs$ in the Baltic Sea drainage area (kBq $m^{-2}$). Modified after De Cort et al. (1998) and HELCOM (2007).

included assays of seawater, fish, and seafloor sediment by HELCOM and national radiation and nuclear safety authorities like STUK of Finland. Chernobyl $^{137}Cs$ fallout peaks in 1986 and then the trend in $^{137}Cs$ contents decline. However, in 2018, $^{137}Cs$ activity contents found in marine mammals, herring, flatfish, and Baltic Sea surface waters remained above the pre-Chernobyl levels interpreted as the environmental baseline (HELCOM, 2018b; Saremi et al., 2018). Man-made radionuclides of particular concern to man and the environment are $^{90}Sr$ and $^{137}Cs$, which are both formed by nuclear fission. With half-lives of about 30 years, these persist in the environment for several centuries once released. Furthermore, $^{90}Sr$ and $^{137}Cs$ are also readily propagated through food chains since strontium and caesium resemble and exhibit similar chemical behavior to calcium and potassium. Humans may become exposed to these radionuclides through ingestion of contaminated food (HELCOM, 2013; UNSCEAR, 2020).

Caesium persists in sediments due to adsorption and fixation by fine particles (e.g. Sawhney, 1972; Cornell, 1993; Delvaux et al., 2000), which makes it important in sedimentological studies. Due to relatively slow rates of water exchange between the Baltic Sea and north Atlantic and the former's relatively rapid rates of sedimentation, radionuclides show prolonged residence times in the Baltic Sea (Ikäheimonen et al., 2009; HELCOM, 2013). Chernobyl fallout created a clear chronostratigraphic marker in Baltic Sea sediments. This $^{137}Cs$ peak has been used widely in dating regional sediments and determining regional rates of sediment deposition (e.g. Kankaanpää, 1997; Kankaanpää et al., 1997; Vallius, 1999; Perttilä et al., 2003; Mattila et al., 2006; Kotilainen et al., 2007; Moros et al., 2017; Virtasalo et al., 2020).

The aims of the study were to determine (1) the levels of $^{137}Cs$ activity content in the seabed sediments of the Gulf of Bothnia, and (2) the spatial and vertical distribution of $^{137}Cs$ in the subsurface sediments. Particular focus is placed on less studied coastal areas, many of which are currently experiencing anthropogenic pressures.

### 1.1. Study area

The Baltic Sea is an epicontinental sea in northern Europe that includes the Gulf of Bothnia as its northernmost body. The Gulf of Bothnia is a relatively shallow area with an average depth of approximately 55 m (Fonselius, 1996). It consists of two sub-basins, the Bothnian Sea to the south and the Bothnian Bay in north. A submarine sill (25 m depth) in the Kvarken (Fig. 1B) separates these two sub-basins.

The Gulf of Bothnia has limited water exchange with the Baltic proper through the Åland Sea and the Archipelago Sea. The Gulf experiences almost no tidal variation and water level fluctuations primarily reflect air pressure, wind, and ice conditions in winter (e.g., Wolski et al., 2014; Johansson and Kahma, 2016). The surface salinity of the Gulf of Bothnia declines from 5–6 PSU in the south to 2–4 PSU in the north (Myrberg et al., 2006). In the northernmost part of the Bothnian Bay, surface salinity approaches 0 PSU (freshwater) due to several rivers that debouche into the bay.

The Gulf of Bothnia basin represents an ancient depression formed within Precambrian crystalline basement rock. These basement rocks are exposed in coastal areas around the Gulf of Bothnia as well as in the Kvarken. Sedimentary rocks predominate in the central part of the Bothnian Sea and the Bothnian Bay (Winterhalter et al., 1981; Koistinen et al., 2001). Crystalline bedrock areas provide more diverse seabed environments than those forming on sedimentary rock (Kaskela and Kotilainen, 2017). During the Weichselian glaciation and local last glacial maximum (LLGM), an ice sheet covered the Gulf of Bothnia and entire Baltic Sea basin. The Gulf of Bothnia deglaciated by ~10 cal. ka BP (Svendsen et al., 2004; Stroeven et al., 2016). Melting of the ice sheets triggered local glacio-isostatic adjustments which continue to this day around the Gulf of Bothnia. The area currently experiences a maximum land uplift rate of 9 mm/year (Ekman, 1996; Kakkuri, 2012).

In the Gulf of Bothnia, less than a third of the seafloor accumulates sediment (Kaskela et al., 2012). Fine grained sedimentary accumulation occurs primarily in deeper areas below the halocline under low-energy conditions and in neritic environments like sheltered basins, archipelagos, and river estuaries (Ignatius et al., 1980; Kotilainen et al., 2012). These patterns appear in seabed substrate data published by EMODnet Geology (2020) (https://hakku.gtk.fi/en/locations/search). In the Gulf of Bothnia, post-glacial rebound continuously raises new material to shallower depths sometimes exposing sediment to active erosion and re-suspension (Kaskela and Kotilainen, 2017). Transport and deposition of sediment derived from current- and wave-induced re-suspension towards deeper basinal areas represent the major sedimentary processes in the basin (e.g. Jonsson et al., 1990; Brydsten, 1993; Christiansen et al., 1997; Moros et al., 2020).

## 2. Materials and methods

Seafloor sediment samples were collected during 2001 to 2019 cruises aboard R/V Geomari, R/V Kaita, and R/V Aranda (Table 1) (Fig. 1). The sampling sites were surveyed primarily using sediment echo sounders or sub-bottom profilers, side scan sonar, and multibeam echosounders (MBE) since 2004. Sampling site locations were selected to represent depositional areas, based on preliminary interpretations of acoustic data and seabed inspection by an underwater video camera. Sediment cores were recovered using a twin barrelled GEMAX gravity corer based on the original Niemistö corer (Niemistö, 1974). The GEMAX corer (Winterhalter, 1998) can recover undisturbed samples even from fluffy, soft mud.

Acrylic sample tubes were removed from the metal corer body on deck. A transparent core line permitted immediate initial observations and sediment description. The sediment core was then split in half lengthwise. The sediment surface was trimmed, photographed, and logged. One half of each sediment core was sliced into 1 cm thick subsamples using a slicing device and then packed into plastic bags and/or boxes. Packed subsamples were stored in the vessel's freezer until landing, transport, and laboratory analysis.

The $^{137}$Cs activity of untreated samples was measured by gamma spectrometry using an EG&E Ortec ACE™-2K spectrometer with a four-inch NaI/TI detector at the Geological Survey of Finland (GTK), Espoo. Since 2017, the $^{137}$Cs activity of sediment samples has been measured for 60 min using a BrightSpec bMCA-USB pulse height analyzer coupled to a well-type NaI(Tl) detector at the Geological Survey of Finland (Ojala et al., 2017). These two methods give rise to slight systematic differences in results which are not considered significant. The $^{137}$Cs activity contents are presented per wet weight (Bq kg$^{-1}$). Amount of measured subsample was 6,65–111,68 g (with an average of 72,41 g).

After the $^{137}$Cs activity measurements, the subsamples were weighed for wet weight, freeze-dried and weighed for dry weight, homogenized and sieved into <2 mm fraction. The subsamples were then analyzed for total carbon (C) using a Leco CHN-600 instrument. Carbonate content is negligible in the northern Baltic Sea; hence, the total C content is considered equal to organic C.

Due to its relatively long radioactive half-life and its affinity for fine sediments, $^{137}$Cs persists in sedimentary records and remains measurable across many sample locations. In undisturbed, non-bioturbated Baltic Sea sediments, a peak in sedimentary $^{137}$Cs (or a sharp $^{137}$Cs increase) is interpreted to reflect the 1986 Chernobyl nuclear disaster (e.g. Meili et al., 1998; Mattila et al., 2006; Zaborska et al., 2014; Moros et al., 2017). Post-Chernobyl sedimentation rates were determined here for all cores using vertical $^{137}$Cs distributions in the sediment cores. Our estimates assumed that the $^{137}$Cs maximum in the sediment corresponds to fallout from the 1986 Chernobyl nuclear power plant accident.

In addition to reporting and interpreting new data, we also include previously published data (Table 1).

Samples collected and measured over different years from 2001 to 2019 gave $^{137}$Cs values representing discrete time frames during the 18 year sampling/measuring interval, and are not fully, directly comparable. Thus, Table 1 lists $^{137}$Cs activity content values decay corrected to 2021.

## 3. Results

Seabed sediment samples were examined from 56 sites around the Gulf of Bothnia (Fig. 1, Table 1). Sediment cores were collected from sites located both in coastal and open water environments. The southernmost site was in the southern Bothnian Sea, and the northernmost site was in the Kemijoki River estuary at the northernmost tip of the Bothnian Bay. Site water depths varied from 4 to 230 m (Table 1).

The length of recovered GEMAX sediment cores varied from 13 to 58 cm with an average length of 39.5 cm. Sediment cores recovered consist primarily of soft, organic-rich, silty clay or clayey silt (Table 1). Coarser material appeared in cores from two sites. Sand specifically occurred in the lowermost part of sediment cores 6 (22 cm) and 1 (14 cm). The sediment cores typically showed oxidized, brownish surface layers that ranged from 1 to 9 cm thick (average 2.9 cm). Surface sediments showed bioturbation with faint remnants of laminae or thin bedded structures beneath the oxic surface layer. At some sites, subsurface sediments appeared laminated without clear signs of bioturbation.

There was no significant correlation between $^{137}$Cs activity and other sediment properties (e.g. water content and total carbon content) (Supplementary Fig. S1). However, total carbon shows a strong positive correlation with water content in sediment. Typical total carbon, water content and $^{137}$Cs profiles in sediment core 35 are shown in Supplementary Fig. S2.

### 3.1. Vertical distribution

Within deeper parts of sediment cores from most sites (49 of 56), $^{137}$Cs activity contents approached values of zero, or close to zero (Figs. 3 and S3). Typically, $^{137}$Cs profiles show a sharp or a relatively sharp upward increase that forms the peak or maximum $^{137}$Cs value.

**Table 1**
Sediment cores from the Gulf of Bothnia reported and interpreted in the present work. Sediment core number (ID); sediment core name; site location (Lat, Lon; WGS84 UTM zone 35N, Lat and Lon in decimal degrees); water depth (m); date of sampling (year/month/date); research vessel (R/V); and $^{137}$Cs activity content in surface sediment (Surface $^{137}$Cs; Bq kg$^{-1}$) with values decay corrected to 2021 shown bolded and italicized in parentheses. Table also lists depth of the maximum $^{137}$Cs activity content in the sediment column (Max depth; cm), maximum $^{137}$Cs activity content from the sediment core (Max $^{137}$Cs; Bq kg$^{-1}$) with values decay corrected to 2021 bolded and italicized in parentheses, post-Chernobyl linear sedimentation rate (Sed. rate; cm/year), and data sources.

| ID | Core | Surface substrate | Lat<br>Lon | Water depth m | Date | R/V | Surface $^{137}$Cs Bq kg$^{-1}$ | Max depth cm | Max $^{137}$Cs Bq kg$^{-1}$ | Sed. rate cm/year | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | MGGN-2018-27 | Gyttja clay | 65,7446<br>24,3420 | 4,0 | 2018/07/31 | Geomari | 18 ***(17)*** | 8,5 | 27 ***(25)*** | 0,3 | This study |
| 2 | MGGN-2019-7 | Gyttja | 65,7397<br>24,3285 | 7,0 | 2019/08/09 | Geomari | 17 ***(16)*** | 9,50 | 50 ***(48)*** | 0,3 | This study |
| 3 | MGGN-2019-8 | Silty gyttja | 65,7371<br>24,1956 | 6,0 | 2019/08/09 | Geomari | 4 ***(3.8)*** | 8,50 | 66 ***(63)*** | 0,3 | This study |
| 4 | MGGN-2018-26 | Gyttja clay | 65,7342<br>24,3040 | 7,0 | 2018/07/31 | Geomari | 23 ***(21)*** | 18,5 | 67 ***(63)*** | 0,6 | This study |
| 5 | MGGN-2018-22 | Gyttja clay | 65,7280<br>24,3759 | 7,0 | 2018/07/30 | Geomari | 1 ***(0.93)*** | 12,5 | 43 ***(40)*** | 0,4 | This study |
| 6 | MGGN-2018-25 | Gyttja clay | 65,7192<br>24,3227 | 8,0 | 2018/07/31 | Geomari | 16 ***(15)*** | 4,5 | 68 ***(63)*** | 0,1 | This study |
| 7 | MGGN-2018-24 | Gyttja clay | 65,7166<br>24,3323 | 8,0 | 2018/07/31 | Geomari | 18 ***(17)*** | 6,5 | 61 ***(57)*** | 0,2 | This study |
| 8 | MGGN-2018-23 | Gyttja clay | 65,7119<br>24,3517 | 10,0 | 2018/07/31 | Geomari | 78 ***(73)*** | 0,0 | 78 ***(73)*** | | This study |
| 9 | MGGN-2018-21 | Gyttja clay | 65,7060<br>24,3862 | 10,0 | 2018/07/30 | Geomari | 16 ***(15)*** | 10,5 | 47 ***(44)*** | 0,3 | This study |
| 10 | MGGN-2018-20 | Gyttja clay | 65,7012<br>24,4094 | 10,0 | 2018/07/30 | Geomari | 23 ***(21)*** | 12,5 | 61 ***(57)*** | 0,4 | This study |
| 11 | MGGN-2017-23A | Silty gyttja | 65,6510<br>24,2880 | 17,7 | 2017/08/09 | Geomari | 13 ***(12)*** | 21,5 | 59 ***(54)*** | 0,7 | This study |
| 12 | MGGN-2017-22A | Silty gyttja | 65,6442<br>24,2112 | 15,8 | 2017/08/09 | Geomari | 6 ***(5.5)*** | 12,5 | 74 ***(67)*** | 0,4 | This study |
| 13 | MGGN-2017-26A | Silty gyttja | 65,6352<br>24,4094 | 17,2 | 2017/08/11 | Geomari | 7 ***(6)*** | 7,5 | *55* ***(50)*** | 0,2 | This study |
| 14 | MGGN-2017-24A | Clayey gyttja | 65,5659<br>24,4582 | 26,5 | 2017/08/10 | Geomari | 0 | 12,5 | 60 ***(55)*** | 0,4 | This study |
| 15 | MGGN-2017-25A | Clayey gyttja | 65,5590<br>24,1660 | 31,2 | 2017/08/10 | Geomari | 15 ***(14)*** | 15,5 | 59 ***(54)*** | 0,5 | This study |
| 16 | MGGN-2019-3 | Silty gyttja clay | 65,3336<br>23,8829 | 55,0 | 2019/08/07 | Geomari | 0 | 13,50 | 72 ***(69)*** | 0,4 | This study |
| 17 | MGGN-2018-17 | Silty clay | 65,3263<br>23,8845 | 56,0 | 2018/07/25 | Geomari | 29 ***(27)*** | 8,5 | 78 ***(73)*** | 0,3 | This study |
| 18 | MGGN-2019-4 | Silty gyttja | 65,2889<br>23,9998 | 59,0 | 2019/08/07 | Geomari | 0 | 26,50 | 76 ***(73)*** | 0,8 | This study |
| 19 | MGGN-2018-18 | Clayey silt | 65,2857<br>23,9754 | 60,0 | 2018/07/25 | Geomari | 27 ***(25)*** | 12,5 | 65 ***(61)*** | 0,4 | This study |
| 20 | MGGN-2019-5 | Gyttja clay | 65,2841<br>23,9591 | 56,0 | 2019/08/07 | Geomari | 29 ***(28)*** | 18,50 | 84 ***(80)*** | 0,6 | This study |
| 21 | MGGN-2019-6 | Gyttja silt | 65,2725<br>24,0246 | 48,0 | 2019/08/07 | Geomari | 13 ***(12)*** | 11,50 | 53 ***(51)*** | 0,3 | This study |
| 22 | MGGN-2018-19 | Silty gyttja | 65,2692<br>24,0068 | 49,0 | 2018/07/25 | Geomari | 21 ***(20)*** | 12,5 | 63 ***(59)*** | 0,4 | This study |
| 23 | MGGN-2019-1 | Clayey gyttja | 64,6249<br>23,5479 | 73,0 | 2019/08/06 | Geomari | 49 ***(47)*** | 2,50 | 106 ***(101)*** | 0,1 | This study |
| 24 | MGGN-2019-2 | Clayey gyttja | 64,6206<br>23,3710 | 72,0 | 2019/08/06 | Geomari | 32 ***(31)*** | 4,50 | 72 ***(69)*** | 0,1 | This study |
| 25 | MGGN-2006-5 | Clayey gyttja | 64,2998<br>22,3295 | 110,0 | 2006/04/22 | Aranda | 799 ***(565)*** | 5,5 | 1712 ***(1211)*** | 0,3 | This study |
| 26 | 44-Ge-02 | Gyttja | 64,0358<br>22,8712 | 41,5 | 2002/07/23 | Kaita | 300 ***(193)*** | 11,5 | 6265 ***(4042)*** | 0,7 | This study |
| 27 | MGGN-2017-28A | Silty gyttja | 63,8774<br>23,0147 | 12,5 | 2017/08/18 | Geomari | 1 ***(0.9)*** | 35,5 | 374 ***(341)*** | 1,1 | This study |
| 28 | 45-Ge-02 | Gyttja | 63,8731<br>23,0088 | 12,7 | 2002/07/24 | Kaita | 131 ***(84)*** | 18,5 | 2082 ***(1343)*** | 1,2 | This study |
| 29 | MGGN-2016-3 | Silty gyttja | 63,3903<br>21,9732 | 25,0 | 2016/08/03 | Geomari | 60 ***(53)*** | 11,5 | 1113 ***(992)*** | 0,4 | This study |
| 30 | MGGN-2016-2 | Silty gyttja | 63,3488<br>22,2472 | 23,0 | 2016/08/03 | Geomari | 107 ***(95)*** | 14,5 | 473 ***(421)*** | 0,5 | This study |
| 31 | VC1 | Gyttja | 63,2851<br>22,2337 | 15,0 | 2011/03/15 | *On the ice* | No_value | 119,0 | 5500 ***(4367)*** | 4,8 | Yu et al., 2015. |
| 32 | 51-Ge-02 | – | 63,2725<br>21,9357 | 12,7 | 2002/07/27 | Kaita | 508 ***(328)*** | 5,5 | 2138 ***(1379)*** | 0,3 | This study |
| 33 | 50-Ge-02 | Gyttja | 63,2401<br>22,0407 | 5,0 | 2002/07/27 | Kaita | 349 ***(225)*** | 14,5 | 7679 ***(4954)*** | 0,9 | This study |
| 34 | | Silty gyttja | | 44,0 | | Geomari | 38 ***(34)*** | 16,5 | 450 ***(401)*** | 0,6 | This study |

(*continued on next page*)

**Table 1** (*continued*)

| ID | Core | Surface substrate | Lat Lon | Water depth m | Date | R/V | Surface $^{137}$Cs Bq kg$^{-1}$ | Max depth cm | Max $^{137}$Cs Bq kg$^{-1}$ | Sed. rate cm/year | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | MGGN-2016-11 | | 63,1691 20,8394 | | 2016/08/05 | | | | | | |
| 35 | MGGN-2016-9 | Silty gyttja | 63,1946 20,8349 | 43,0 | 2016/08/05 | Geomari | 105 ***(94)*** | 18,5 | 331 ***(295)*** | 0,6 | This study |
| 36 | MGGN-2016-13 | Sandy gyttja | 63,1883 20,8812 | 34,0 | 2016/08/05 | Geomari | 93 ***(83)*** | 6,5 | 256 ***(228)*** | 0,2 | This study |
| 37 | MGGN-2016-10 | Silty gyttja | 63,1748 20,8093 | 45,0 | 2016/08/05 | Geomari | 38 ***(34)*** | 20,5 | 522 ***(465)*** | 0,7 | This study |
| 38 | MGGN-2018-29 | Gyttja clay | 63,1497 21,2094 | 16,8 | 2018/08/08 | Geomari | 45 ***(42)*** | 15,5 | 395 ***(367)*** | 0,5 | Virtasalo et al., 2020. |
| 39 | MGGN-2018-30 | Silty gyttja | 63,1337 21,2388 | 14,2 | 2018/08/08 | Geomari | 60 ***(56)*** | 8,5 | 285 ***(266)*** | 0,3 | Virtasalo et al., 2020. |
| 40 | MGGN-2016-4 | Silty gyttja | 63,1176 21,3458 | 11,0 | 2016/08/04 | Geomari | 59 ***(53)*** | 20,5 | 373 ***(332)*** | 0,7 | This study |
| 41 | MGGN-2017-17 | Gyttja | 63,1138 21,3930 | 10,0 | 2017/06/30 | Geomari | 72 ***(66)*** | 16,5 | 290 ***(264)*** | 0,5 | Virtasalo et al., 2020. |
| 42 | MGGN-2016-7 | Silty gyttja | 63,1124 21,5422 | 5,0 | 2016/08/04 | Geomari | 46 ***(41)*** | 8,5 | 121 ***(108)*** | 0,3 | This study |
| 43 | MGGN-2018-32 | Silty gyttja | 63,1112 21,2739 | 15,1 | 2018/08/10 | Geomari | 101 ***(94)*** | 5,5 | 220 ***(205)*** | 0,2 | Virtasalo et al., 2020. |
| 44 | MGGN-2017-20 | Gyttja clay | 63,1107 21,5364 | 5,0 | 2017/07/03 | Geomari | 27 ***(25)*** | 13,5 | 174 ***(159)*** | 0,4 | Virtasalo et al., 2020. |
| 45 | MGGN-2017-21 | Gyttja | 63,1095 21,5622 | 4,0 | 2017/07/04 | Geomari | 27 ***(25)*** | 9,5 | 61 ***(56)*** | 0,3 | This study |
| 46 | MGGN-2018-31 | Silty gyttja | 63,1068 21,2316 | 17,5 | 2018/08/10 | Geomari | 70 ***(65)*** | 7,5 | 205 ***(191)*** | 0,2 | Virtasalo et al., 2020. |
| 47 | MGGN-2017-18 | Gyttja | 63,0963 21,4556 | 8,0 | 2017/06/30 | Geomari | 37 ***(34)*** | 21,5 | 310 ***(283)*** | 0,7 | Virtasalo et al., 2020. |
| 48 | MGGN-2017-19 | Gyttja | 63,0926 21,5094 | 7,0 | 2017/07/03 | Geomari | 25 ***(23)*** | 12,5 | 247 ***(225)*** | 0,4 | Virtasalo et al., 2020. |
| 49 | MGGN-2016-6 | Silty gyttja | 63,0918 21,4794 | 7,0 | 2016/08/04 | Geomari | 44 ***(39)*** | 14,5 | 252 ***(225)*** | 0,5 | This study |
| 50 | MGGN-2016-8 | Silty gyttja | 63,0840 21,5364 | 6,0 | 2016/08/04 | Geomari | 32 ***(29)*** | 39,5 | 165 ***(147)*** | 1,3 | Virtasalo et al., 2020. |
| 51 | MGGN-2003-11 | Gyttja clay | 63,0817 21,2089 | 12,0 | 2003/08/01 | Kaita | 462 ***(305)*** | 3,5 | 1074 ***(709)*** | 0,2 | This study |
| 52 | MGGN-2003-10 | Gyttja clay | 63,0807 21,1432 | 13,6 | 2003/07/31 | Kaita | No_value | 4,5 | 2546 ***(1681)*** | 0,3 | This study |
| 53 | KV-01-4 | – | 63,0624 21,2795 | 7,1 | 2001/09/28 | Kaita | 77 ***(49)*** | 7,0 | 309 ***(195)*** | 0,5 | This study |
| 54 | MGGN-2016-14 | Gyttja clay | 62,5942 19,9861 | 147,0 | 2016/08/07 | Geomari | 84 ***(75)*** | 14,5 | 310 ***(276)*** | 0,5 | This study |
| 55 | MGGN-2016-15 | Clayey gyttja | 62,5863 19,9686 | 230,0 | 2016/08/07 | Geomari | 101 ***(90)*** | 44,5 | 343 ***(306)*** | 1,5 | This study |
| 56 | MGGN-2006-3 | Clayey gyttja | 61,0685 19,7302 | 130,0 | 2006/04/20 | Aranda | 1047 ***(741)*** | 7,5 | 1466 ***(1037)*** | 0,4 | This study |

Values then decrease gradually towards the sediment surface (Fig. 3E–N). Most sediment cores clearly showed these subsurface $^{137}$Cs activity content maxima. Some sites (8 of 56) exhibited a minor peak in $^{137}$Cs contents below the maxima (Fig. 3A–D). Those sites (cores 2, 4, 8, 9, 10, 11, 12, and 13) occur in the northern Bothnian Bay near the Kemijoki and Tornionjoki estuaries.

Six sediment cores showed increasing $^{137}$Cs contents downcore without clear maxima. The lack of maxima may arise from their young age range (Fig. 3O and P).

The results of $^{137}$Cs contents are reported here with decay corrected values to the year 2021 in parentheses. The maximum $^{137}$Cs contents in sediment cores varied from 27 (25) to 7679 (4954) Bq kg$^{-1}$ with an average maximum concentration of 516 Bq kg$^{-1}$ (Figs. 4, 5, and 7; Table 1). The highest $^{137}$Cs values (>4000 Bq kg$^{-1}$) appeared in cores from the Kvarken area in Kyrönjoki estuary (core 33, 7679 (4954) Bq kg$^{-1}$), the Vöyrinjoki estuary (core 31, 5500 (4367) Bq kg$^{-1}$), and the Bothnian Bay offshore of the city of Kokkola (core 26, 6265 (4042) Bg kg$^{-1}$). The lowest maximum $^{137}$Cs values (<60 Bq kg$^{-1}$) appeared in sediment cores from the northern Bothnian Bay (Figs. 5 and 7).

Maximum $^{137}$Cs values in the sediment cores occurred from 0 to 199 cm depths with an average depth of 15.1 cm for maximum $^{137}$Cs contents (Figs. 3, 4 and S3, and Table 1). The deepest example of a $^{137}$Cs maxima occurred in sediment cores from coastal sites of the Vöyrinjoki estuary (core 31, 119 cm), Korshamnsfjärden in the Kvarken archipelago (core 50, 39.5 cm), and a bay in the vicinity of Kokkola city (core 27, 35.5 cm). Open water sites of the Köysimonttu depression (230 m deep) in the northern Bothnian Sea (core 55, 44.5 cm) and Hailuoto channel/canyon in the northern Bothnian Bay (core 18, 26.5 cm) also exhibited relatively deep $^{137}$Cs maxima. The depths of $^{137}$Cs maxima in cores indicate relatively high sedimentation rates. Post-Chernobyl linear sedimentation rates varied from 0.1 to 4.8 cm/year with an average value of 0.54 cm/year (Table 1).

Maximum values for $^{137}$Cs activity in surface sediments varied from 0 to 1047 (741) Bq kg$^{-1}$ with an average value of 100 (73) Bq kg$^{-1}$ (Figs. 4 and 6, Table 1). The highest $^{137}$Cs content observed in surface sediments (>150 Bq kg$^{-1}$) occurred in the southern Bothnia Sea (Site EB1, core 56; 1047 (741) Bq kg$^{-1}$), in the central Bothnian Bay (Site BO3, core 25; 799 (565) Bq kg$^{-1}$), in the Kvarken archipelago (cores 32 and 51; 508 (328) Bq kg$^{-1}$ and 462 (305) Bq kg$^{-1}$, respectively), in Kyrönjoki estuary (core 33; 349 (225) Bq kg$^{-1}$), and in the Bothnian Bay offshore of Kokkola city (core 26; c. 300 (193) Bq kg$^{-1}$). The lowest $^{137}$Cs (<30 Bq kg$^{-1}$) values occurred in surface sediments from sediment

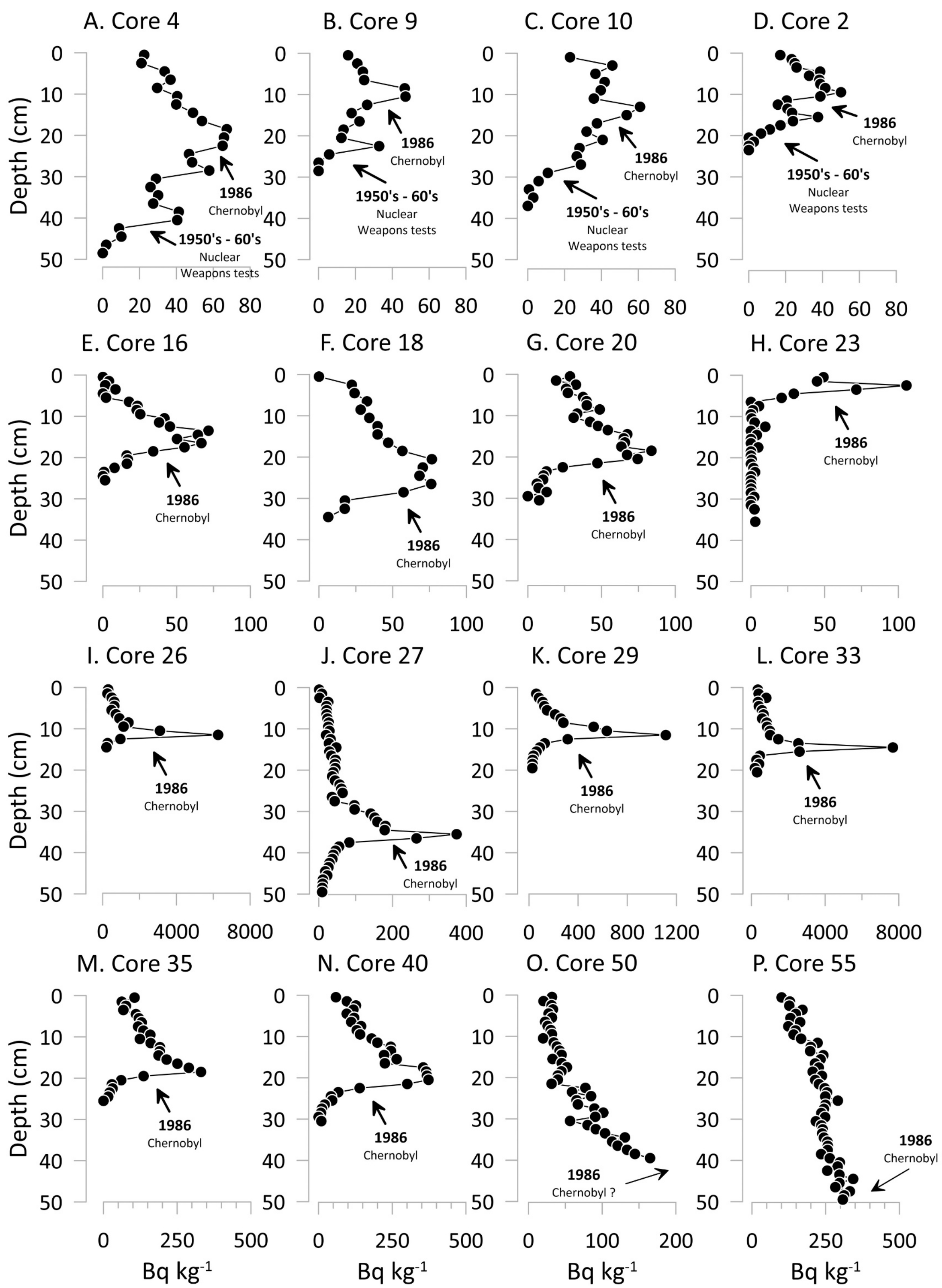


**Fig. 3.** $^{137}$Cs activity contents (Bq kg$^{-1}$) down-core vs. depth profiles from selected sediment cores (A–P) taken in the Gulf of Bothnia. Stratigraphical marker horizons are labelled, and ages are given in years AD.

cores from the northern Bothnian Bay north of 65°16 N latitude (Figs. 6 and 7).

Generally, seafloor sediments from the northernmost reaches of the Bothnian Bay exhibited the lowest $^{137}$Cs activity contents.

## 4. Discussion

### 4.1. Vertical distribution of $^{137}$Cs in Gulf of Bothnia sediments

The shape of $^{137}$Cs distributions in sediment profiles resembles a typical sediment profile measured from undisturbed Baltic Sea sediments and indicates relatively continuous recent accumulation. Values of $^{137}$Cs approach zero in deeper parts of sediment cores collected from

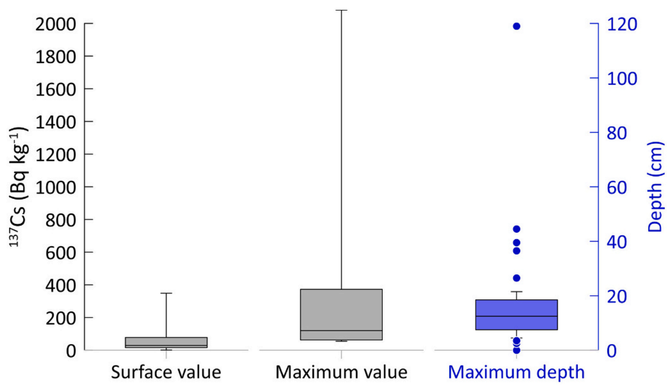


**Fig. 4.** $^{137}$Cs (Bq kg$^{-1}$) activity contents in surface sediments (left), maximum $^{137}$Cs values (Bq kg$^{-1}$) in sediment cores (center), and depth (cm) of maximum $^{137}$Cs values (right, blue). Number of samples is 56. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

most sites. This indicates that sediment cores sample recent sediments as well as older sediments deposited prior to the commencement of nuclear weapons testing (i.e. before the atomic bomb time, that is before 1945 CE).

A subsurface $^{137}$Cs maximum is apparent in most of the sediment cores studied. The relatively steep, upward increase towards the $^{137}$Cs maximum indicates an immediate and discrete event and is thus consistent with Chernobyl fallout. Several marine and lake sediment studies in the Baltic Sea and its catchment area have verified by dating and other methods that the $^{137}$Cs maximum (or a sharp increase in $^{137}$Cs values) represents Chernobyl fallout (e.g. Reinikainen et al., 1997; Kotilainen et al., 2007; Jokinen et al., 2015; Ojala et al., 2017; Moros et al., 2017). The sediment cores analyzed here show partly laminated or thin bedded sedimentary fabrics in intervals that host the sharp upward increase in $^{137}$Cs values. Sediment cores that did not show this sharp upward increase approaching the maxima showed bioturbation. Macrofaunal burrowing activities (e.g. Virtasalo et al., 2011) at these sites appears to have disturbed chemostratigraphic signatures. In addition to bioturbation, diffusion might have caused post-depositional downward transport of $^{137}$Cs in sediments (Holby and Evans, 1996; Klaminder et al., 2012; Ojala et al., 2017). The shape of the curve and $^{137}$Cs maxima are clearly identifiable in most of the cores analyzed, bioturbation and/or diffusion notwithstanding.

A smaller $^{137}$Cs peak appears below $^{137}$Cs maxima in eight sediment cores (Fig. 3A–D). We interpret this feature to represent material derived from atomic bomb testing. The sediment cores exhibiting the lesser, older $^{137}$Cs peak occur in the vicinity of the Kemijoki and Tornionjoki estuaries, which occupy the northernmost reaches of the Bothnian Bay. It is possible that the similar evidence of atomic bomb fallout is also recorded in sediments elsewhere in the Gulf of Bothnia, but downward diffusion of Chernobyl-derived $^{137}$Cs has partly masked the older feature. Chernobyl-derived $^{137}$Cs contents are also more abundant in sediments collected from southerly localities. Studies of lake sediments from these regions show similar patterns (Ojala et al., 2017). Earlier studies have interpreted radionuclide content in Baltic Sea sediments as originating from nuclear weapons tests (e.g. Salo and Tuomainen, 1986; Moros et al., 2017). The majority of atmospheric nuclear weapons tests occurred during the late 1950s and early 1960s resulting in a peak of Northern Hemisphere atmospheric $^{137}$Cs deposition in 1963 (Pennington et al., 1973). Salminen-Paatero et al. (2019) report that hardly any refractory or intermediate radionuclides from the Chernobyl event appear in Finnish Lapland. The main source of $^{137}$Cs and $^{90}$Sr and total beta activity detected in the atmosphere around Rovaniemi from 1965 to 2011 is interpreted to derive from intense atmospheric nuclear weapon testing in 1950s and 1960s and later tests performed from 1965 to 1980. Leaks from underground nuclear tests in Semipalatinsk in 1966 and Novaya Zemlya in 1987 also represent sources (Salminen-Paatero et al., 2019). We therefore interpret the minor $^{137}$Cs peak observed in sediment from the northernmost Bothnian Bay as arising from river transport of atomic test derived $^{137}$Cs fallout from the Tornionjoki and Kemijoki catchment areas of Sweden and Finland.

Six sediment cores show $^{137}$Cs values increasing downcore suggesting that the $^{137}$Cs concentration maxima were probably not reached/recovered in sediment sampled by the corer (Fig. 3O and P). This also indicates high sediment deposition rates at those sites. Also, Yu et al.

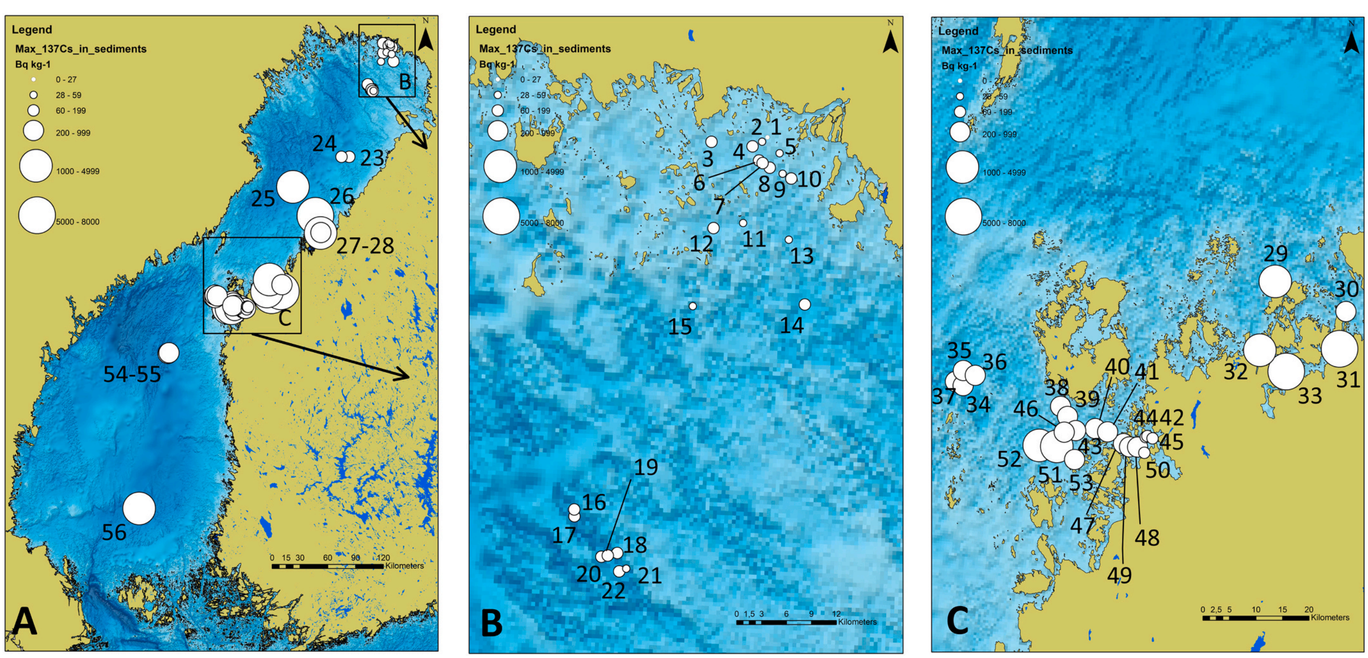


**Fig. 5.** A. The maximum$^{137}$Cs contents (Bq kg$^{-1}$) in subsurface sediments according to cores from the Gulf of Bothnia. White dots and numbers (1–56) show the locations of sampling sites. B. The maximum$^{137}$Cs contents (Bq kg$^{-1}$) in subsurface sediments in cores from the northern Bothnian Bay, and C. the Kvarken archipelago. Bathymetry data: HELCOM, BSHC (Baltic Sea Bathymetry).

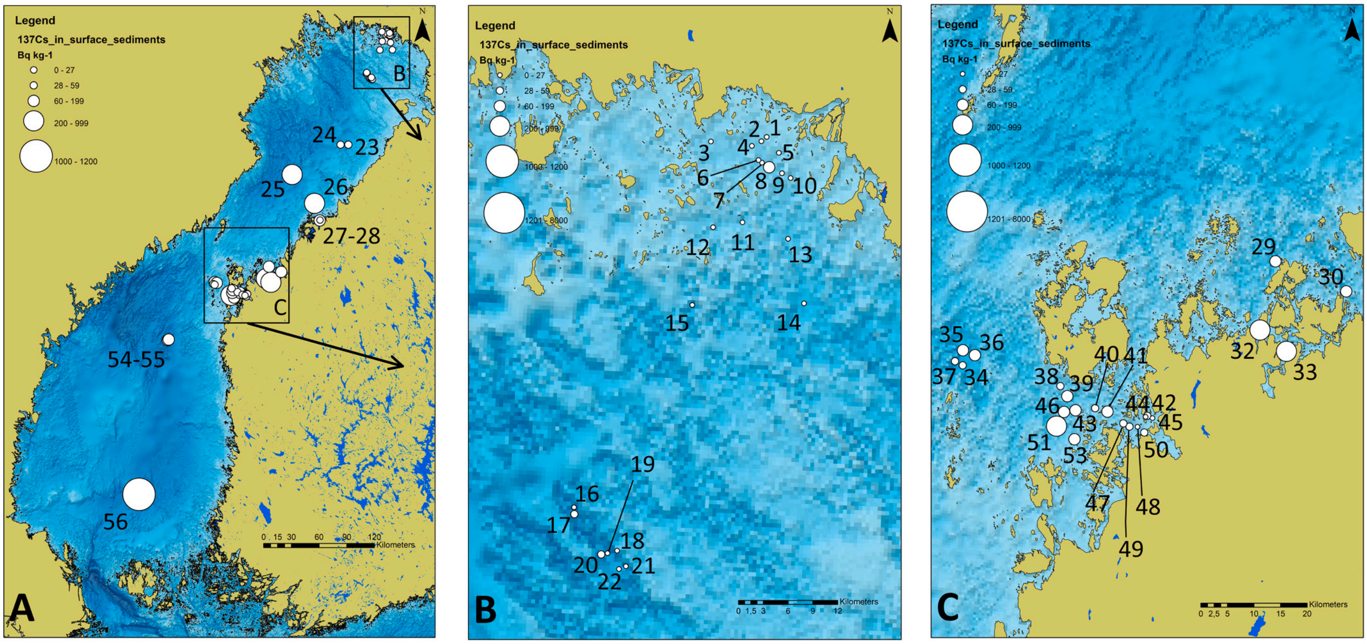


**Fig. 6.** A. The maximum $^{137}$Cs contents (Bq kg$^{-1}$) in surface sediments according to cores from the Gulf of Bothnia. White dots and numbers (1–56) show the locations of sampling sites. B. The maximum $^{137}$Cs contents (Bq kg$^{-1}$) in surface sediments in cores from the northern Bothnian Bay, and C. the Kvarken archipelago. Bathymetry data: HELCOM, BSHC (Baltic Sea Bathymetry).

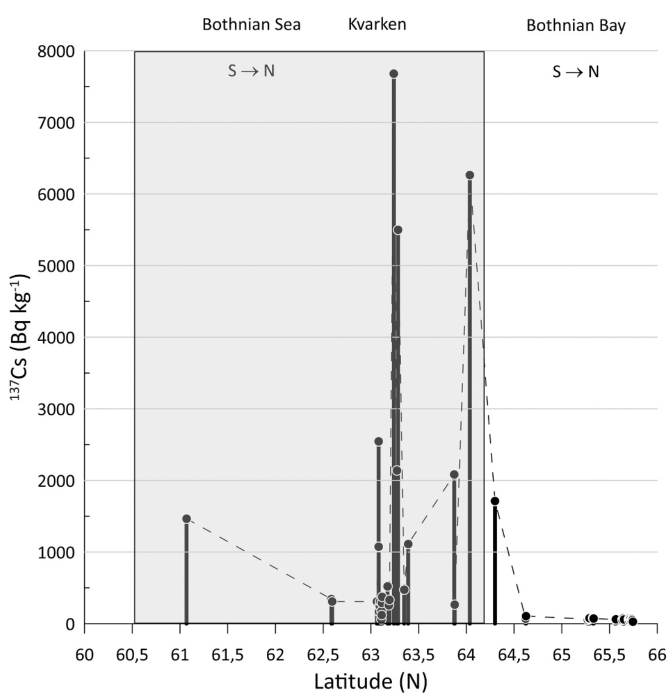


**Fig. 7.** Maximum $^{137}$Cs (Bq kg$^{-1}$) values in sediments analyzed from the Gulf of Bothnia area. Samples ordered along a south-north latitudinal gradient. Latitudes are shown in decimal degrees. Grey area in the figure indicates the latitudinal area along the coast of Finland exposed to the most intensive $^{137}$Cs fallout from the 1986 Chernobyl event (also shown in Fig. 2; data: STUK; HELCOM, 2007).

(2015) reported very high deposition rates in the area, in Vöyrinjoki estuary, where $^{137}$Cs maximum was observed 119 cm deep in the sediment.

In almost all sediment cores, above the $^{137}$Cs maximum, $^{137}$Cs values decrease gradually towards the sediment surface. However, surface sediment $^{137}$Cs values exceed background (pre-nuclear weapons tests) values suggesting that surface sediments continue to receive $^{137}$Cs inputs mobilized via river discharge from catchment soils and via resuspension in shallow coastal areas. Wind-generated waves, ice, and currents in shallow coastal areas erode and resuspend bottom sediment. Along with river loads, this material can be transported to calmer, deeper areas via surface and bottom currents. In the Baltic Sea, the sedimentation often occurs below the halocline (60–80 m) and wave base (Winterhalter et al., 1981; Kohonen and Winterhalter, 1999; Jönsson et al., 2005; Myrberg et al., 2006). In deeper areas, sporadic, strong bottom currents can also erode the seabed (e.g. Moros et al., 2020).

### 4.2. *Chernobyl derived $^{137}$Cs in Gulf of Bothnia sediments*

The highest $^{137}$Cs values observed in sediment occurred in coastal areas, especially near river estuaries including the Kyrönjoki and Vöyrinjoki estuaries and the Kvarken archipelago (Fig. 5, Table 1). High $^{137}$Cs values in subsurface sediments also occur in the southern Bothnian Sea, the Gloppet (in the Kvarken archipelago), the southern Bothnian Bay, and in the vicinity of Kokkola city. Even though nearly every sample analyzed showed $^{137}$Cs values positionally above the $^{137}$Cs maximum decreasing up core towards the present-day sediment surface, these values remain well above baseline in many areas. Subsurface sediments around the Baltic Sea store relatively high levels of $^{137}$Cs even after the passage of up to two $^{137}$Cs half-lives. The lowest $^{137}$Cs maximum occurred in sediment cores from the northern Bothnian Bay. Results from the present study show spatial consistency with terrestrial deposition patterns in Chernobyl-derived $^{137}$Cs around the Baltic Sea drainage area (kBq m$^{-2}$) as shown in Figs. 2 and 7. Elevated $^{137}$Cs values in subsurface sediments occur within and around areas exhibiting high $^{137}$Cs fallout. Surface sediments show similar $^{137}$Cs distributions with the highest contents in the southern Bothnian Sea, the southern Bothnian Bay, the Gloppet (Kvarken archipelago), and in Kyrönjoki and in Vöyrinjoki estuaries of the Kvarken archipelago (Fig. 6, Table 1). These results are consistent with previous studies that have documented the highest $^{137}$Cs values in seafloor sediments around the northern Bothnian Sea and southern areas of the Bothnian Bay. Beyond the Gulf of Bothnia, the highest $^{137}$Cs values in seafloor sediment occur in the eastern Gulf of

Finland (HELCOM, 2003, 2007, 2009, 2013; Ilus, 2007).

Elevated $^{137}$Cs values in bottom sediments of estuaries or around river mouths, with catchment areas exposed to high levels of Chernobyl-derived $^{137}$Cs fallout, document the role of fluvial transport (e.g. Brydsten and Jansson, 1989). Estuaries can host thick post-Chernobyl sediment layers in which the Chernobyl $^{137}$Cs maximum lies deep within the sediment column. Elevated $^{137}$Cs levels in sediment indicate rapid deposition of particles having adsorbed $^{137}$Cs (Nagao et al., 2013; Taniguchi et al., 2019). Mixing with seawater in estuaries results in partial desorption of $^{137}$Cs from suspended particles into a dissolved phase. However, a significant proportion of fluvial $^{137}$Cs remains adsorbed to fine fraction of suspended particles and therefore subject to transport across estuarine gradients towards the marine environment (Takata et al., 2015; Kakehi et al., 2016; Takata et al., 2020). Indeed, sediments with larger fine-grained fractions tend to accumulate more $^{137}$Cs (e.g. He and Walling, 1996; Yoshimura et al., 2014). In addition to river transport of $^{137}$Cs, direct atmospheric deposition of Chernobyl $^{137}$Cs fallout also likely occurred. Gradual decline in $^{137}$Cs values above $^{137}$Cs maxima in sediment cores suggest continuous, post-Chernobyl $^{137}$Cs transport, deposition, and potential re-mobilization. Particles transported to coastal depocenters by rivers can be further eroded, resuspended and re-deposited by currents. Sediments around Kvarken archipelago for example show metal enrichment from acid sulphate soils at least 25 km seaward from river mouths (Virtasalo et al., 2020).

Concentrations in the seawater show also decreasing trends over the time. Based on the average concentrations of $^{137}$Cs calculated for period 2011–2016 for surface seawaters, the highest average concentration of $^{137}$Cs equal to 29.3 Bq m$^{-3}$ was found in the Bothnian Sea. These values are much lower compared to the distribution of $^{137}$Cs in surface waters after the Chernobyl accident, when in the most contaminated areas (the Bothnian Sea and the Gulf of Finland) activities exceeding 500 Bq m$^{-3}$ were observed (HELCOM, 2018b). In the recent HELCOM inventory (2011–2015), it was estimated that the total amount of $^{137}$Cs activity in the Baltic Sea sediments was about 2200–2500 TBq. This amount is about 8–9 times higher compared to the amounts of the pre-Chernobyl level at the beginning of the 1980s (HELCOM, 2013). In recent years, $^{137}$Cs has continued to deposit onto bottom sediments and, at the same time, the physical half-life reduces the activities slowly. Most of the $^{137}$Cs activity is found in the seabed of the Bothnian Sea and in the eastern Gulf of Finland (HELCOM, 2018a).

### *4.3. Post-Chernobyl sedimentation in the Gulf of Bothnia*

In addition to serving as a chronostratigraphic indicator, sedimentary $^{137}$Cs can also help constrain recent rates of sedimentation (e.g. Kankaanpää, 1997; Kankaanpää et al., 1997; Vallius, 1999; Perttilä et al., 2003; Mattila et al., 2006; Kotilainen et al., 2007; Moros et al., 2017; Virtasalo et al., 2020). We calculated the linear sedimentation rate estimates here using the subsurface depths of the $^{137}$Cs maxima for a placement of the Chernobyl event. In some sites, a placement of 1986 at the marked $^{137}$Cs increase could have been more appropriate than the placement at the $^{137}$Cs maximum (see Fig. 3). Thus, sedimentation rate estimates reported here are the minimum sedimentation rates. The highest sedimentation rates detected by this study occurred in estuaries. These include the Vöyrijoki estuary (core 31, 4.8 cm/year), Korshamnsfjärden (Laihianjoki and Sulvanjoki estuary) (core 50, 1.3 cm/year), offshore of Kokkola city (core 27, 1.1 cm/year), and the Kyrönjoki estuary (core 33, 0.9 cm/year). The high rates of sedimentation observed in estuaries demonstrate the importance of fluvial transport and flocculation processes in estuarine environments. Estuaries can filter nutrients, organic matter, metals, radionuclides, and other pollutants out of river discharge to marine environments (e.g. Billen et al., 1991; Bouwman et al., 2013; Asmala et al., 2017; Jilbert et al., 2018; Carstensen et al., 2020).

Similar to estuaries, pelagic environments in the Gulf of Bothnia exhibit high rates of sedimentation. These include deep basins like the Köysimonttu depression (230 m deep) in the northern Bothnian Sea (core 55, 1.5 cm/year) and canyons like Hailuoto channel in the northern Bothnian Bay (core 18, 0.8 cm/cm).

Post-Chernobyl linear sedimentation rates at sites studied around the Gulf of Bothnia varied from 0.1 to 4.8 cm/year with an average value of 0.54 cm/year (Table 1). The Gulf of Bothnia, however, consists of a very heterogeneous seafloor especially in coastal zones which host a mosaic of erosional and depositional features (Kotilainen et al., 2012; Kaskela and Kotilainen, 2017). Seafloor heterogeneity likely reflects variation in sedimentation rates (e.g. Mitchell et al., 2021). As shown here, deep basins including sea holes and canyons become depocenters for fine-grained sediment deposition in the deeper areas, and estuaries and archipelagos in the coastal zone. Observations may also reflect the fact that sites exhibiting high rates of sedimentation according to soundings received priority, in the sampling site selection process. Sites thus likely represent upper estimates of sediment deposition for the entire study area.

The average short-term sedimentation rate of 0.54 cm/year estimated here for the Gulf of Bothnia resembles sedimentation rates of 0.35 and 0.62 cm/year (surface sediment layer) previously reported for the Bothnian Bay and Bothnian Sea, respectively (Mattila et al., 2006). These values typically exceed long-term sedimentation rates reported for deeper basins of the Baltic Sea. The deep basins and depressions tend to represent deposition on millennial time scales whereas coastal areas exhibit significant sedimentation on decadal-centennial time scales. Erosion leads to smaller millennial scale deposition rates for coastal areas. In the Gulf of Bothnia, Häusler et al. (2017) estimated a linear sedimentation rate of 1.3 mm/year for the last 7000 years. Hille et al. (2006) reported recent sedimentation rates of ca. 0.93 ± 0.67 mm/year for the Eastern Gotland Basin. Other reports give similar estimates of long-term deposition rates for this area. Ignatius et al. (1971) estimated a linear sedimentation rate of 1 mm/year over the last 7000 years, and Kotilainen et al. (2000) estimated linear sedimentation rates between 0.38 and 0.88 mm/year for the past 3000 years. Researchers have estimated linear sedimentation rates of ca. 0.83 mm/year for the North Central Basin over the past 3000 years (Kotilainen et al., 2001), ca. 3.7 mm/year for the Landsort Deep over the past 11,000 years (Obrochta et al., 2017), and ca 1.2 mm/year for the Western Gotland Basin over the past 6000 years (Moros et al., 2020). Compaction of sediments may lead to slightly lower estimates for long-term deposition rates relative to estimates for surface sediments. While sedimentation rates referred here represent average values, sediment deposition shows considerable spatial and temporal variation (e.g. Kotilainen et al., 2000; Winterhalter, 2001; Hille et al., 2006; Mattila et al., 2006; Nuorteva and Kankaanpää, 2016).

### *4.4. Seabed sediments and coastal zone management*

Many areas around the Gulf of Bothnia experience severe anthropogenic pressure. Seafloor sediments show elevated levels of $^{137}$Cs (this study) and heavy metals (e.g. Vallius, 2015; Virtasalo et al., 2020). $^{137}$Cs has generally declined over the last decades and natural background radioactivity predominates both dose rates and doses except for those measured in 1986. Individual dose rates in some regions of the Baltic Sea approached background levels even in the presence of Chernobyl fallout (Nielsen, 2000). Coastal areas, like estuaries, however, still show elevated levels of $^{137}$Cs in subsurface sediments due to continuous fluvial transport from surrounding areas.

Human activities that modify the seafloor include dredging of shipping lanes and harbours, landfill excavation, dumping of materials, and construction of offshore wind farms. Human activity has altered extensive areas of the shoreline around the northern Bothnian Bay in the recent past. This activity often includes small-scale dredging (Sahla et al., 2020).

Dredging resuspends sediments, thereby increasing the suspended matter concentration in the water column and exposing finer particles to transport by currents. In the Gulf of Finland, material suspended by dredging in Neva Bay can be transported all the way to Vyborg Bay (Sukhacheva et al., 2016). Fine-grained material can bind harmful substances like $^{137}$Cs and heavy metals. Disposal of contaminated soils in the marine environment results in similar dispersal effects. The increased level of caesium in surface sediments is also due to the increased concentration of caesium in water as a result of anthropogenic pollution of the Baltic Sea.

Estuaries and other coastal environments such as shallow coastal bays and lagoons represent valuable natural and cultural resources which perform a significant range of ecosystem services. Studies have identified Finnish coastal estuaries and coastal lagoons as threatened habitat types. The second assessment of threatened habitat types in Finland classified coastal estuaries as 'Endangered' based on their long-term degradation. Acidification of river water, river pollution, dredging, and construction have all contributed the degradation of estuaries (Kotilainen et al., 2018).

Marine spatial planning must consider risks that attend anthropogenic uses of marine areas. Disruption of the seafloor in areas subject to long term pollution represents a major risk. While planners generally understand that bottom sediments can contain pollutants, understanding of the exact type, location, and concentration of pollutants in bottom sediments remains vague. Future research should seek to constrain these parameters especially in the coastal areas experiencing increased anthropogenic pressures. Data on harmful substances can inform coastal management and marine spatial planning by noting risks associated with construction or other activities that may disrupt the seafloor. Anthropogenic pressures on marine and coastal environments are likely to increase in the future. Climate change will also shift sea level, hydrology, temperature, and other parameters which shape the marine environment. Effective response to these changes must include a detailed understanding of risks lurking in sediment.

## 5. Conclusion

This report describes and interprets $^{137}$caesium ($^{137}$Cs) activity contents in seafloor sediment samples from 56 sites around the Gulf of Bothnia, northern Baltic Sea.

Activity contents of $^{137}$Cs in sediment have generally declined over the last decades. In some coastal areas such as estuaries however, $^{137}$Cs values in subsurface sediments remain at elevated levels relative to values measured from other areas of the Baltic Sea. The highest $^{137}$Cs activity contents (>4000 Bg kg$^{-1}$) in sediment occurred in coastal areas associated with river estuaries, including Kyrönjoki and Vöyrinjoki estuary of the Kvarken archipelago. Elevated $^{137}$Cs values in subsurface sediments also occur in the southern Bothnian Sea, the Gloppet (Kvarken archipelago), the southern Bothnian Bay, and in the vicinity of Kokkola city.

Elevated $^{137}$Cs values in subsurface sediment appear in areas that experienced the highest levels of Chernobyl-derived $^{137}$Cs fallout. Similar lateral distribution can be also seen in surface sediments. Vertical distributions of $^{137}$Cs in Gulf of Bothnia core material indicate that the radionuclide derives mainly from the 1986 Chernobyl nuclear power plant accident.

A minor peak in $^{137}$Cs activity contents appears below the $^{137}$Cs maxima in sediment cores from the northernmost parts of the Bothnian Bay, including the Kemijoki and Tornionjoki estuaries. We interpret this feature as reflecting nuclear weapons testing in the 1950s and 1960s.

In addition to chronostratigraphic constraints, sedimentary $^{137}$Cs distributions provide estimates for recent rates of deposition. Post-Chernobyl linear sedimentation rates around the Gulf of Bothnia varied from 0.1 to 4.8 cm/year with an average value of 0.54 cm/year. Sediments from coastal areas showed the highest rates of sedimentation. These occurred in sediments from Vöyrijoki estuary, in Korshamnsfjärden close to Vaasa city (Laihianjoki and Sulvanjoki estuary), from the bay near Kokkola city, and in the Kyrönjoki estuary. Several open water areas in the Gulf of Bothnia also showed high rates of sedimentation. These include deep basins like the Köysimonttu depression in the northern Bothnian Sea and canyons found in the northern Bothnian Bay.

Data on harmful substances (e.g. $^{137}$Cs) in seafloor sediments can inform coastal management and marine spatial planning efforts to assess risk associated with construction in marine areas. Dredging in areas where sediments contain high concentrations of radioactive materials can cause re-mobilization and transport of these contaminants. Increasing anthropogenic pressures in marine and coastal areas will likely increase risk associated with polluted sediment. Climate change will also likely shift many of the parameters that affect sediment distribution and pollution in the Gulf of Bothnia as well.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112924.

## Data availability

All data is available in Table 1 of the article, and in PANGAEA database (link).

## CRediT authorship contribution statement

Aarno Kotilainen: Planning the study, Writing – original draft, Investigation, Analysis, Funding acquisition. Mia Kotilainen: Writing – review and editing. Vesa-Pekka Vartti: Writing – review and editing. Kaisa-Leena Hutri: Writing – review and editing. Joonas Virtasalo: Writing – review and editing, Investigation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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