

# Core-derived historical records of suspended sediment origin in a mesoscale mountainous catchment: the Bléone River French Alpas

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2	RESEARCH ARTICLE
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4	Core-derived historical records of suspended sediment origin in a mesoscale
5	mountainous catchment: the Bléone River, French Alps
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## 35 Abstract

**Purpose:** Quantifying suspended sediment fluxes and dynamics across mountains and identifying the origin of sediment in severely eroded areas are of primary importance for an equilibrate management of water resources. This contribution aims at generalising previous results of suspended sediment fingerprinting obtained during the 2007-2009 period in a mesoscale Alpine catchment, the Bléone River (905 km<sup>2</sup>) and to possibly check their validity throughout the second half of the 20<sup>th</sup> century.

42 **Materials and methods:** Sediment fingerprinting based on elemental geochemistry and 43 radionuclide measurements was conducted on a sediment core collected in an alluvial 44 floodplain at the basin outlet. This technique was combined with long hydro-sedimentary 45 time-series to reconstruct the origin of suspended sediment that deposited at this location 46 throughout the last 50 years.

47 Results and discussion: Hydro-sedimentary interpretation of sedimentation based on historical hydrological databases corroborates core dating obtained with <sup>137</sup>Cs and <sup>210</sup>Pb<sub>xs</sub> 48 49 activity measurements. Black marls and (marly) limestones provided the bulk of sediment 50 throughout the sequence (40% and 22%, respectively), while they only occupies 10% of the 51 total catchment area. However, we also showed the occurrence of major floods carrying large 52 quantities of sediment originating from Quaternary deposits and conglomerates (25% and 53 16%, respectively). The variability of sediment sources throughout the sequence may reflects 54 the spatial variability of rainfall within the catchment, depending on air mass origin. 55 However, the relatively homogeneous sediment composition throughout the sequence 56 confirms that core-derived information is representative of large-scale flood events.

57 **Conclusions:** In conclusion, these results are consistent with the ones obtained in previous 58 studies. They also outline the need to take account of the entire grain size range of fine 59 sediment to provide an overall picture of sediment sources and transfers within highly erosive 60 catchments. This study finally emphasize the relevance of using archive data to validate 61 sediment fingerprinting generally conducted during short monitoring programs across larger 62 time period and large widespread floods.

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64 Keywords Braided river • Erosion • Geochemistry • Radionuclide • Sediment core •
65 Sediment fingerprinting

- 66
- 67
- 68 **1 Introduction**

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69 In mountainous regions, hillslope erosion and mass movements supply large quantities of 70 fine-grained sediment (< 63  $\mu$ m) to rivers where they generally cause numerous 71 environmental and economical problems, such as reservoir siltation and operational problems 72 for hydroelectric power plants (e.g., Valero-Garcés et al. 1999). An excess of sediment supply 73 can also lead to an increase in water turbidity, eutrophication and degradation of riverine 74 habitats in lowland areas (e.g. Owens et al. 2005). Furthermore, although suspended sediment 75 conveys the biogenic elements required by all the living organisms, the finest fraction (< 6376 µm) is also one of the main vectors of contaminant transfer (e.g., PCBs, heavy metals) within 77 catchments (Owens and Walling 2003; Collins et al. 2005).

78 The Rhône River that flows across Switzerland and France has become the main sediment 79 supplier to the Mediterranean Sea since damming of the Nile River (Sempéré et al. 2000). 80 Downstream reaches of this river are confronted with particularly severe contamination and 81 siltation problems (Antonelli et al. 2008; Sicre et al. 2008). Previous studies hypothesised that 82 a significant part of sediment probably originated from the badland areas constituted of black 83 marls and located in the Durance River catchment (e.g. Pont et al. 2002; Di Giovanni et al. 84 2002). During the 3-year STREAMS (Sediment TRansport and Erosion Across MoutainS) 85 research project funded by the French Research Agency, a large hydro-sedimentary database 86 was compiled in the Bléone River catchment (905 km<sup>2</sup>) which is one of the main contributor 87 of sediment to the Durance River (Mano et al. 2009). The catchment is equipped with 7 hydrometric stations at intermediary scales (i.e., 10-1000 km<sup>2</sup>). Each station is characterised 88 89 with high frequency acquisition of discharge and turbidity, and suspended sediment sampling 90 during floods. This network provided a useful complement to the existing installations of the 91 Draix Observatory that have been used since 1985 to investigate sediment dynamics in small 92 (< 1 km<sup>2</sup>) severely eroded headwater catchments (Mathys et al. 2003). Sediment 93 fingerprinting studies were conducted in this catchment to better understand the dynamics and to define the origin of the suspended sediment in the catchment. Evrard et al. (2011) and 94 95 Navratil et al. (2012) outlined the very large spatial and temporal variability of sediment sources and exports during this study period. The preliminary results showed that 80% of 96 97 suspended sediment was produced by floods generated by widespread low-intensity rainfall 98 across the catchment. Such result corroborates the conclusions of Duvert et al. (2010, 2011). 99 Furthermore, the analyses of several 1-2 yrs return period floods and one major flood (10 yrs-100 return period flood) that occurred in a subcatchment confirmed the important contribution of 101 black marls (up to 70%) to sediment transported in rivers, although this substrate only 102 occupies ca. 10% of the total catchment surface. Sediment exports generated by local

103 convective storms varied significantly at both intra- and inter-flood scales, because of spatial 104 heterogeneity of rainfall. However, black marls/marly limestones contribution remained 105 systematically high. In contrast, widespread flood events that generate the bulk of annual 106 sediment supply at the outlet were characterised by a more stable lithologic composition and 107 by a larger contribution of limestones/marls, Quaternary deposits and conglomerates (Navratil 108 et al. 2012).

109 In order to validate those findings over a longer time period and to enlarge the scope of 110 our fingerprinting study to a larger set of weather and flood conditions, we investigated the 111 evolution of suspended sediment origin and dynamics over a 50-year period from the severely eroded Bléone river catchment (905 km<sup>2</sup>). To this end, we collected a sediment core in the 112 113 alluvial floodplain at the Bléone catchment outlet. Long-term meteorological and 114 hydrological datasets were used to interpret the structure of this core and to associate the 115 sediment deposits with different hydrological periods. Radionuclide and elemental 116 geochemistry properties were then measured on the core sediment samples. A mixing model 117 was finally used to trace the origin of suspended sediment transported during a selection of 118 past large floods.

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# 121 2 Study area

The Bléone catchment (905 km<sup>2</sup>; lat.: 44°05'34''N, long.: 06°13'53''E), with altitude 122 123 ranging between 405 and 2961 m A.S.L. (Above Sea Level), is a mountainous Alpine 124 catchment located in the Durance River district, in southeastern France (Fig. 1). The 125 catchment is characterised by a dendritic drainage network dominated by the Bléone River 126 and several tributaries, among which the Bès River (233 km<sup>2</sup>-subcatchment) is the most 127 important. Forest is by far the main land use in the catchment (44% of the total catchment 128 surface; Table 1). The lithology mainly consists of marls, molasses and limestones, with large 129 areas of exposed Cretaceous and Jurassic black marls, as well as Lias marly limestones (Fig. 130 2). Geological information was derived from a digitised 1:50,000 spatially-distributed 131 geological map of the catchment provided by the French Geological Survey (BRGM). Eroded 132 surfaces (covering 11% of the total Bléone catchment area, see Fig. 2) were delineated in a 133 GIS using aerial photographs taken during flight campaigns conducted in 2004 by the French 134 National Geographic Institute (IGN). Eroded surfaces cover a mean surface of 0.45 km<sup>2</sup> (between 811 m<sup>2</sup> and 1.85 km<sup>2</sup>) and were classified into three groups: debris slope areas (22% 135 136 of the eroded areas), sheet and rill erosion areas (48%), and gully erosion areas (30%). Areas

137 covered by black marls are strongly affected by erosion and are characterized by a badland138 morphology (Mathys et al. 2005).

139 The climate is transitional and undergoes mountainous and Mediterranean influences. Mean 140 annual temperature ranges between 12-13°C at 400 m A.S.L., with high temperature 141 variations between summer and winter (about 18°C). Mean annual rainfall in the catchment 142 varies between 600-1200 mm at 400 m A.S.L. According to local archives (Archives 143 Départementales des Alpes de Haute Provence), the largest historical flood at the basin outlet 144 is reported to have occurred in July 1854, with a peak discharge estimated at ~1,100 m<sup>3</sup> s<sup>-1</sup> (Sogreah, 2005). Over the past decades, the maximum specific peak discharges were 145 146 significantly higher in the Bès River subcatchment (165 km<sup>2</sup>) than in other similar catchments of the Southern French Alps (Fig. 3c): 3.6 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup> for the Bès River, against less than 1.4 147  $m^3 s^{-1} km^{-2}$  in other catchments. This subcatchment has therefore a very specific behaviour. 148 149 Furthermore, floods that occurred in this area from 1960 to 2009 were characterised by a 150 strong seasonality. Most of the floods occurred in autumn (see Fig. 3a). South or South-151 Western atmospheric fluxes originating from the Mediterranean Sea and characterised by 152 humid and warm air flows provide the bulk of annual rainfall in this region. They triggered 153 most of the largest floods observed since 1960 (see Fig. 3b). The presence of a widespread 154 depression centered on France is also associated with heavy rainfall in the entire country and 155 generates large and widespread floods at the basin scale. In contrast, Western weaker 156 depressions coming from the Atlantic Ocean generally dry up over the first French mountain 157 ranges (i.e., Massif Central and Pyrénées), so that they only provide low-intensity rainfall 158 when they reach the Southern Alps. Northern and North-Western fluxes occur when the 159 Azores High is located at high latitudes; midlatitude cyclones can then arrive from the 160 Northern Alps and produce the bulk of the snow cover. Eastern fluxes are associated with a 161 high pressure cell standing over central Europe. Contact between this cold and dry air mass 162 with the Mediterranean air mass can trigger particularly heavy storms over the Southern Alps 163 in spring and summer. Finally, when high pressure cells dominate in the region, local 164 convective storms can also occur due to local air mass instability (Gottardi 2009). These 165 storms mostly occur between June and September. They are associated with heavy downpours 166 that may trigger flash floods and debris flows that are otherwise restricted to small headwater 167 streams.

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#### 170 3 MaterialS and methodS

### 171 **3.1 Coring site**

172 A 3-meter long sediment core (5-cm diameter) was collected on 26 November, 2009 with 173 a Cobra corer in the Bléone River floodplain, upstream of the Malijai dam close to the outlet 174 (see Fig. 1b; 905 km<sup>2</sup>). Coring was conducted in collaboration with the Laboratoire de 175 Géophysique Interne et Tectonophysique (LGIT) and the Laboratoire des Sciences de 176 *l'Environnement* (LSE). The sampling site was selected on a vegetated bar composed of very 177 fine sediment, adjacent to the river channel, and located about 1 meter above the mean floodplain level. During floods, water level and flow velocity are controlled so as to ensure 178 179 good operating conditions for the dam. In the recent period, we observed that the floodplain 180 was systematically submerged during the largest floods. There was no evidence of bank 181 erosion in the vicinity of the coring site. We therefore hypothesize that this site located within 182 the dam reservoir has underwent a slow sedimentation since the dam building.

183 Malijai dam was built by the French national electricity producer (EDF) in 1962. During base 184 flow periods, the dam is closed to divert part of the clear water into a canal. To limit supply of 185 sediment and associated substances to the downstream Berre lagoon (Accornero et al. 2008), 186 French authorities fixed a maximal suspended sediment concentration that can be delivered to 187 the canal, which leads to extra management costs for the company exploiting the power 188 plants. Consequently, during floods, the dam is opened manually in order to divert water and 189 sediment into the main channel. Sediment siltation mainly occurs during large floods (>1-2 190 yrs return period) in the reservoir area where we sampled the sediment core. From 1962 191 onwards, the dam has accumulated sediment, whereas resuspension of fine sediment and 192 bedload only occurred in the middle part of the active river channel (see Fig. 1b).

193

# 194 **3.2 Stratigraphic structure of the sediment core**

In this study, we used X-ray measurements and visual observations to outline the stratigraphic structure of the core, i.e. the succession of flood deposits since the Malijai dam construction (1962).

The core was X-rayed at the *Eaux Claires* Hospital of Grenoble, with the aim to associate specific densities with grey level intensities (de Montety et al. 2003). Longitudinal image resolution was 2 mm; mean and standard deviation of grey level intensities were then measured in each section (i.e. horizon) within a 2 by 2 cm window centered on the core axis. Grey shades are considered to reflect the density of sediment as the grey-scale intensity of an X-ray image is proportional to beam attenuation of the incident X-ray (Lofi and Weber 1999). The grey intensity variations in that core would therefore undoubtedly reflect the succession of flood deposits (i.e., varves).

Then, the sediment core was cut into two longitudinal parts, photographed, and subsampled based on two strategies: (1) sections were made following the stratigraphic structures of varves detected by X-ray analysis and visual observation, on the first half of the core; (2) 2cm wide sections were cut on the second half of the core. Sediment samples were ground to a fine powder and dried at 105°C for 2 hours.

Then, we measured the grain-size of a selection of core samples to analyse the inter- and intra- varve variations of grain-size fraction. Subsamples were analysed with a Malvern<sup>®</sup> particle laser sizer after 7-min of stirring and sonication. Grain size distributions and statistics were computed with Gradistat software (Blott and Pie 2001).

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# 216 **3.3 Origin of fine sediment**

# 217 3.3.1 Soil and core sediment sampling

Representative soil samples were collected in the Bléone basin to characterize potential source materials (see Evrard et al. 2011 for details). They were taken mostly on colluvial toeslopes adjacent to the drainage network to be representative of material eroded from adjacent hillslopes. Soil samples were dried at  $105^{\circ}$ C and disaggregated prior to analysis. As the core sediment samples have a finer grain size than the soil samples (i.e., potential sediment sources), we sieved this source material to <63 µm before conducting radionuclide and geochemical analyses (Navratil et al. 2012).

We used the 2-cm core section samples (n = 92 for the core dating and n = 34 for the sediment fingerprinting) to cover the entire sequence of sediment deposit. The sediment samples were dried at 40°C, disaggregated and sieved to  $63\mu m$ .

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# 229 3.3.2 Measurement of radionuclide and elemental geochemistry

230 In total, we measured gamma-emitting radionuclide activity in 92 core samples and 231 the 150 source samples. Sediment was placed in a counting box when there was sufficient material (≥10 g). Radionuclide activities (<sup>241</sup>Am, <sup>137</sup>Cs, <sup>40</sup>K, <sup>210</sup>Pb, <sup>226</sup>Ra, <sup>228</sup>Ra, <sup>234</sup>Th, <sup>228</sup>Th) 232 233 were determined by gamma-spectrometry using the very low-background coaxial N- and P-234 types GeHP detectors (Canberra / Ortec / Eurisys) available at the Laboratoire des Sciences 235 du Climat et de l'Environnement (Gif-sur-Yvette, France). Efficiencies and background levels 236 of the detectors were periodically controlled with internal and IAEA (International Atomic 237 Energy Agency) soil and sediment standards (Evrard et al. 2010; Evrard et al. in press). When 238 there was < 10 g sediment available, filters were placed in tubes and counting was conducted 239 at the Laboratoire Souterrain de Modane (LSM; CNRS-CEA) under the French Alps, using a 240 very low background, high-efficiency well-type Ge detector (Reyss et al. 1995).

241 For the measurement of elemental geochemistry, dried subsamples (c. 80 mg) of selected 2-242 cm core sections (n = 34) were analysed by inductively coupled plasma – mass spectrometry 243 (ICP-MS; XII CCT Series, Thermo Electron), in solutions containing 0.2 g of solid L<sup>-1</sup>. The 244 sediment total digestion procedure is described by Le Cloarec et al. (2011). Concentrations 245 were determined for five major (Al, K, Fe, Mg, Ti) and thirteen trace (Ag, Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb, Tl, V, Zn) elements. The accuracy of the elemental concentration 246 247 determination was evaluated through the repetitive analysis of the certified reference material 248 SL-1 (lake sediment, AIEA, Vienna, Austria). The obtained values (n=4), agreed with the 249 certified concentrations, when available. Certified values are not available for Ag, Al, Ca, Mg 250 and Tl. The accuracy of the determination of these four elements in SL-1 was cross-checked 251 with values determined by neutron activation analysis (Ayrault et al. 2010; Evrard et al. 252 2011). Analytical uncertainties associated with this method did not exceed 20 and 10% for 253 major and trace element determination, respectively. Analysis of source material is described 254 in detail in Navratil et al. (2012).

255

### 256

# 3.3.3 Selection of fingerprints and design of a mixing model

257 Based on the French Geological Survey (BRGM) map of the catchment (see Fig. 2), 258 we grouped the geological classes represented on the map and corresponding to our sediment 259 source samples types into 5 classes: (1) marly limestones; (2) limy marls; (3) conglomerates; 260 (4) Quaternary deposits; (5) black marls (see Evrard et al. 2011). As described by Navratil et 261 al. (2012), we selected 10 fingerprinting properties that can discriminate between these five 262 different sediment sources. Among them, 6 properties were sufficient to design the optimum composite fingerprint. Only one geogenic radionuclide was pointed out (<sup>226</sup>Ra). The other 263 264 selected fingerprints were V, Ni, Mn, Sb and Cu. Then, we constructed a Monte Carlo mixing model as detailed by Navratil et al. (2012) in order to quantify the contribution of each 265 266 sediment source to the core sediment samples.

267

#### 268 **3.4 Core dating**

269 Dating of the sediment cores relied on the measurement of two radionuclides (i.e., <sup>137</sup>Cs and <sup>210</sup>Pb<sub>xs</sub>) that strongly sorb onto fine sediment (Owens at al. 1999). <sup>137</sup>Cs was used as 270 an event-tracer, whereas <sup>210</sup>Pb<sub>xs</sub> provided the sediment age (Appleby 2000). Both 271

radionuclides are gamma emitters and they can be detected without any previous chemicaltreatment of sediment.

<sup>137</sup>Cs is an artificial radionuclide ( $t_{1/2} = 30$  years) produced by the thermonuclear bomb testing conducted between the 1950s and the 1980s (with a maximum input in 1963) and, depending on local weather conditions, after the Chernobyl accident in 1986. <sup>137</sup>Cs is now stored in soils, and this <sup>137</sup>Cs stock decreases by radioactive decay and by fine sediment transfer to the rivers.

278 Uncertainty on measurements was ca. 0.5%, and the detection limits reached 0.3 Bq kg<sup>-1</sup>.

<sup>210</sup>Pb is a natural radionuclide ( $t_{1/2} = 22.3$  years) which is a decay product of <sup>238</sup>U ( $t_{1/2} = 4.5 \times 10^9$  years). <sup>238</sup>U decays through a series of short-lived nuclides (e.g., <sup>226</sup>Ra and <sup>222</sup>Rn). <sup>222</sup>Rn is a gas that partly remains *in situ*, forming "supported" <sup>210</sup>Pb, and that partly escapes to the atmosphere, forming "excess" <sup>210</sup>Pb, which reaches the soil surface by wet and dry fallout. It then strongly sorbs to soil particles. The activity in "excess" <sup>210</sup>Pb was calculated by subtracting the supported activity (determined using a <sup>238</sup>U daughter, i.e. <sup>214</sup>Bi) from the total activity of <sup>210</sup>Pb. Uncertainty on measurements was thus higher than for <sup>137</sup>Cs (ca. 10%).

Sedimentation rates were then calculated based on the Constant Rate Supply (CRS) model(Appleby and Oldfield 1983).

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#### 289 **3.5** Climatological and hydro-sedimentary databases

290 Classically, core interpretation involves a count-from-the-top correlation of the 291 individual flood deposits with flood events that resulted in overbank deposition (e.g. Hobo et 292 al. 2010). However, evident difficulties prevented to associate each individual varve with 293 individual flood events: (1) the context of this study (mountainous river with flash floods, 294 complex sedimentation due to dam functioning) and (2) the lack of long-term water-295 level/discharge time-series available at the coring location. We therefore analysed the 296 correlation between the stratigraphic structure of the core (succession of varve thickness) and 297 the inter-annual hydro-meteorological variations. Given the lack of discharge data available at 298 the Bléone River outlet, we compiled data from various sources available at different spatial 299 scales and temporal resolutions to interpret the flood deposits at the Bléone River outlet: 300 databases of rainfall time-series, discharge and suspended sediment concentration time-series 301 and historical floods and mass movements.

Ten rain-gauges managed by the *Laboratoire d'étude des Transferts en Hydrologie et Environnement* (R1–R5) and the French *Cemagref* research agency (R6–R10) provided continuous precipitation records (see Fig. 1; Table 1). Five meteorological stations managed by the French meteorological office (i.e., *Météo France*) provided rainfall depths and durations, snow depth, temperature as well as information on the occurrence of storm or hail
events (R11–R15). Four of them provided daily rainfall for the 1960-2009 period (R11, R12,
R14, R15; Table 1). These last stations only provided daily records (with the exception of one
station, i.e., R12, providing hourly records). Altogether, these data provided good information
about spatial and temporal variability of rainfall at the Bléone River basin scale.

311 Discharge, suspended sediment concentration (SSC) and yields (SSY) were measured at 1-h 312 time steps by EDF at the Malijai station during the 2001-2003 and 2007–2009 periods (Table 313 1). Discharges were measured on the Bès River at Pérouré station (165 km<sup>2</sup>; see Fig. 1) during 314 the 1963–2009 period. SSC have been measured with turbidimeters since October 2007 - see Navratil et al. (2010) and Navratil et al. (2011) for more information about SSC and SSY 315 316 equipments and methods. Discharge, SSC and SSY have also been measured at three other 317 stations within the catchment (i.e., Duyes River at Mallemoisson, Galabre River at Robine, 318 Bléone River at Prads) since October 2007 (see Fig. 1; Table 1). Discharge and sediment have 319 also been monitored since 1985 in the Draix Observatory managed by Irstea in Grenoble. We 320 took into consideration the data from the monitoring station of the Laval torrent  $(0.86 \text{ km}^2)$ 321 available since 1985 and still ongoing (Mathys et al. 2003; see Fig. 1; Table 1).

322 We also used a database of field observations made available by the office in charge of 323 mountain area restoration in France (i.e., Restauration des Terrains en Montagne service 324 (RTM) of the French National Forest Office; RTM, 2010). Important historical information 325 has been compiled since 1351 in the Bléone River basin (i.e., the oldest information of 326 torrential flood available): the occurrence of avalanches, rock falls, debris flows, torrential 327 floods and landslides. In this study, we extracted from this database the annual frequency of 328 debris flows/flash floods and landslides observed in the Bléone catchment since 1960 to 329 document erosion intensity within the Bléone catchment throughout time.

330

## 331 4 Results and discussion

# 332 **4.1**<sup>210</sup>Pb<sub>xs</sub> and <sup>137</sup>Cs dating

Gamma spectrometry countings conducted at Gif-sur-Yvette and Modane laboratories provided very complementary results. We observed a decay of  $^{210}$ Pb<sub>xs</sub> with depth in the sediment core when taking all 92 analysed samples into account (Fig. 4) even though precision obtained on activities was larger on the 45 samples analysed in Modane, because of the very low level of background at this underground laboratory (se Fig. 4). Sedimentation rate could be calculated based on  $^{210}$ Pb<sub>xs</sub> decay of activities and was estimated at 5.4 cm yr<sup>-1</sup> along the first 150 cm, and at 4 cm yr<sup>-1</sup> if we take the entire depth of the core into account.

Activities in <sup>137</sup>Cs provided additional information to date the core. Peak activities were 340 341 measured between 278 and 288 cm depths (32–44 Bq kg<sup>-1</sup>). Peak associated with the bomb fallout (maximum activity in 1963) usually reaches values  $\geq$  30–35 Bq kg<sup>-1</sup> (e.g., Le Cloarec 342 343 et al., 2011; Perga et al., 2010), which remains consistent with our findings. Furthermore, presence of  $^{241}$ Am (ca. 1 – 1.5 Bq kg<sup>-1</sup>) could be detected at this depth (265–290 cm), 344 345 confirming the bomb origin of <sup>137</sup>Cs fallout. In contrast, <sup>137</sup>Cs activity peak associated with Chernobyl fallout in 1986 could not be detected. This peak absence can be justified by the 346 347 very low cumulative rainfall amount (i.e., 9 mm) observed in the Bléone catchment when the 348 radioactive cloud flew over the area (i.e., between 30 April – 4 May according to the cloud 349 dispersion model developed by French Radioprotection and Nuclear Safety Institute (IRSN 350 2011).

Overall datation of the core was therefore obtained by combining the sedimentation rate derived from  $^{210}$ Pb<sub>xs</sub> decay and the location of the bomb  $^{137}$ Cs activity peak in depth (see Fig. 4c). We can note that the date of the bottom of the core corresponds to the Malijai dam building (i.e., 1962). These results only provide an indicative dating of the core, as we hypothesised a constant rate of sedimentation since 1962. Erosion rate varies between seasons and years depending on flood magnitude. This point will be explored in detail with the hydrosedimentary interpretations.

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#### 359 **4.2 Stratigraphic structure of the sediment core**

360 In total, 114 varves corresponding to variations of grey shades on the X-ray images 361 were detected (Fig. 5a, b). These layers were confirmed by visual description of the core after 362 opening. Mean varve thickness reaches 2 cm, but it fluctuates between 0.2 and 13 cm. The 363 sediment core is characterised by about 7 cycles having similar stratigraphic structures, i.e. a 364 succession of several small varves (< 2 cm) followed by one to three larger varves (ranging 365 from 2-13 cm). The layer located between 91-102 cm could not be analysed because of 366 technical problems during field sampling. Oblique varves observed between 162-198 cm depth cannot be attributed to a disturbance of the core during sampling or transport. We will 367 368 discuss its possible origin in section 5.

369

# 370 **4.3 Hydro-sedimentary interpretations**

The 1962-2009 discharge time-series available for the Bès River at Pérouré station (165 km<sup>2</sup>; Fig. 6c) provide information on flood occurrence within the catchment. However, because of the spatial heterogeneity of rainfall across the catchment, these data do not 374 systematically reflect the flood magnitude at the Bléone River outlet (905 km<sup>2</sup>). At the scale 375 of the entire catchment, only qualitative information about flood occurrence is available 376 (Sogreah 2005; RTM 2010; Fig. 7a). Nine major floods that led to infrastructure damages 377 have been reported by mountainous area restoration office (RTM) at the outlet of the Bléone 378 River catchment since 1970s (i.e., in July 1973, March 1974, January 1978, October 1979, 379 1992, 1993, January, September and November 1994). In January 1994, a 10-years return period flood was observed (Sogreah 2004; ~ 400 m<sup>3</sup> s<sup>-1</sup>). The peak discharge observed on the 380 Bès River at Pérouré was about 41 m<sup>3</sup> s<sup>-1</sup> (i.e., a two-year return period flood) but the Bès 381 River subcatchment was not included in the area of maximum rainfall intensity. Two 382 383 additional 10-years return period floods were observed in November 1994 and 2000 at the 384 Bléone River outlet. The corresponding peak discharges observed on the Bès River at Pérouré 385 indicate that they were associated with a two-year return period at this station.

386 Furthermore, to obtain additional data at the river basin scale, we analysed the inter-annual 387 variation of rainfall based on information provided by the different rain-gauges available 388 within the catchment (see Table 1). A moving average (window size of one year; lag time of 6 389 months) was applied to monthly rainfall data (see Fig. 6a) and to the maximum daily intensity 390 of each month (see Fig. 6b). No significant pluri-annual trend could be retrieved for the 1960-391 2009 period. We therefore defined "wet" years (i.e., with mean rainfall > 900 mm yr<sup>-1</sup> and 392 mean interannual rainfall intensity > 25 mm day<sup>-1</sup>; see Fig. 7b) and "dry" years (i.e., with mean rainfall < 900 mm yr<sup>-1</sup> and mean interannual rainfall intensity < 25 mm day<sup>-1</sup>; see Fig. 393 394 7c). A pluri-annual cycle (mean period of ca. 3-5 years) with alternance/succession of "wet" 395 and "dry" years can thereby be outlined (see Fig. 7 b, c). These periods were found consistent 396 with the occurrence of large floods (Sogreah 2005; RTM 2010; see Fig. 7a), the hydrometric 397 stations records (see Table 1) and the database of the hydro-sedimentary activity (RTM 2010; 398 see Fig. 7a).

399 We can now attempt to correlate the flood deposits with inter-annual hydro-meteorological 400 patterns by a two-step count-from-the-top method (Hobo et al. 2010). In the first step, the largest flood deposits were correlated with the occurrence of "wet" years and the largest 401 402 floods. In the second step, the smallest intermediate varves were correlated with the "wet" and 403 "dry" years that occurred between the major events. This correlation method is based on 404 several assumptions: (1) the largest floods would be responsible for the deposition of the 405 thickest varves (Hobo et al. 2010); (2) the "wet" years are the most likely periods for the 406 occurrence of large floods at the Bléone River basin scale (905 km<sup>2</sup>); (3) other small and 407 large-scale floods can also occur during the same period, but deposits from two or more

floods in the same hydrological season may sometimes not be identified separately. Sediment deposits are indeed likely to be remobilised during the next flood, unless they are fixed by vegetation during the growing season (Hobo et al. 2010); (4) 'dry' years can be associated with small/moderate overbank floods at the core location and may result in thinner varyes.

412 Varve thickness distribution matches well with the variability of the hydro-sedimentary time-

413 series (see Fig. 7d). The largest varves, i.e., between the horizons 230-260 cm, 150-220 cm, 414 80-110 cm and 30-50 cm, clearly correspond to the largest floods that occurred during the 415 "wet" periods, respectively during the periods 1968-1973, 1977-1981, 1992-1994, 1999-2002. 416 In contrast, the thinnest varves correspond to low magnitude floods that occurred during 417 "wet" and "dry" periods: 1960-1967, 1974-1976, 1982-1991, 1995-1998, 2003-2009. The 418 oblique varves observed between 160-200 cm are likely to correspond to the collapse of the 419 river bank at that location and can be associated with the widespread flood that occurred in 420 1979 (RTM 2010).

The grain-size fraction (<2 mm) is variable (Fig. 8a), with a dominance of silt-clay sized fraction throughout the core (ca. 80%). The mean D50 is 18.5  $\mu$ m (range from 0.7 - 84  $\mu$ m); the mean D10 is 2.3  $\mu$ m (range from 0.16-22.7  $\mu$ m) and the mean D90 is 160  $\mu$ m (<1000  $\mu$ m). Sand fraction is higher between 120-250 cm (ca. 30%). This core section could correspond to the large floods documented during the 1970s (1973, 1978, 1979 floods; see Fig. 3c) thereby confirming our previous interpretation.

427

# 428 **4.4 Sediment core fingerprinting**

Results of the mixing model showed that sediment sources varied during the last 50 years for the selected core sections (see Fig. 8b). Globally, black marls and (marly) limestones provided the bulk of sediment throughout the sequence: on mean 40% for black marls (min. = 19% and max = 71%) and on mean 22% for limestones (min = 14%; max = 34%). Major floods can also generate huge quantities of sediment originating from Quaternary deposits and conglomerates (respectively, 25% (min = 3%, max = 54%) and 16% (min = 6%, max = 28%)).

According to this model, black marls and limestones provided the bulk of sediment during the 1960s (51–88%). Then, during the 1970s, sediment origin was much more equilibrate between material supplied by a mix of black marls, limestones, Quaternary deposits and conglomerates. In 1972–1973, a flood was characterized by sediment originating mainly from Quaternary deposits (84% of sediment), indicating the likely occurrence of mass movements in the catchment. After this event (between 1974–1978), we calculated again a mixed 442 contribution of four substrate types to the Bléone River sediment with a clear dominance of 443 Quaternary deposit contribution in 1974. In 1979, a major flood occurred. At this horizon, we 444 observed a series of vertical varves, indicating the collapse of the river bank at that location. 445 Major mass movements are likely to have occurred during this period, as indicated by the 446 dominant contribution of Quaternary deposits and conglomerates to sediment deposited in 447 between 1970-1981. As reported from the hydrological time-series, rainfall data and past 448 observations (RTM 2010), this period was very active in terms of sediment transport. Several 449 other subsequent floods supplied sediment originating from Quaternary deposits and 450 conglomerates up to 1985. During the other floods that were analysed in detail, black marls 451 and (marly) limestones provided the bulk of sediment (36–85%), together with a mix of 452 conglomerates and Quaternary deposits. Deposits corresponding to 1991, 1993 and 2006 were 453 almost exclusively provided by black marls and marly limestones (74–89%). These variations 454 of sediment origin can be mainly attributed to the spatial variability of rainfall in the 455 catchment that triggered torrential floods, but also to the magnitude of the flood and its 456 capacity to remobilise the fine sediment temporarily stored in the river channel and 457 floodplain. Furthermore, the relative homogeneity of sediment composition within the core 458 (coefficient of variation of 31, 22, 61, 30% respectively for black marls, limestones, 459 Quaternary deposits, conglomerates) confirm that the core-derived information rather reflect 460 the occurrence of widespread and large-scale floods, with a contribution of all sediment 461 sources available in the catchment rather than the sediment export triggered by local storm 462 events.

These results are in agreement with the sediment flux time-series recorded at the Laval Torrent at Draix (drainage area of 0.86 km<sup>2</sup>; Fig. 9). This site was indeed characterised by massive exports of black marl material (Mathys et al. 2003) in 1992, 1994, 1996 and 2004 and 2006. These floods probably provided the flood deposits observed between 85-105 cm depth and 28-35 cm depth in the core. For the other sites, only very limited data were available and they only covered the end of the study period (i.e., 2007-2009) characterised globally by a low sediment export at the Bléone outlet.

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# 471 **4.5** Comparison with flood scale analyses conducted during the 2007-2009 period

These results can be compared to previous findings obtained by sediment fingerprinting on both riverbed and suspended material collected in the Bléone River catchment during a more recent period (2007-2009; Fig. 10; Evrard et al. 2011; Navratil et al. 2012).

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476 Analysis of the core deposits and the suspended sediment outlined very similar trends at the 477 catchment outlet (see Fig. 10). Black marl contribution clearly dominates, providing a mean 478 of 40% for the core deposits and 34% for the suspended sediment. Given this substrate only 479 occupies 10% of the total catchment area, it underlines the high erodibility of black marls 480 (e.g., Mathys et al. 2005; Poulenard et al. 2012). Limestones/marly limestones contributions 481 are also significant (mean of 22% for core deposits and 30% for suspended sediment), but 482 they remain in the same order of magnitude as the % of catchment surface that they occupy 483 (ca. 37 %). It confirms the lower erodibility of those substrates compared to black marls. 484 Analysis of core deposits and suspended sediment also remain consistent regarding 485 Quaternary deposits (21 % vs. 23%, respectively). This contribution corresponds once again 486 to the % of occurrence of those substrates within the catchment (ca. 27%). The lowest 487 contribution corresponds to conglomerate sources (mean of 13% vs. 16%), whereas it 488 occupies about 25% of the catchment. In contrast, black marls and limestones are under-489 represented in riverbed sediment compared to their occurrence within the catchment, whereas 490 Conglomerates and Quaternary deposits are over-represented in this material.

The grain size of these different sources may explain this variability, even though we could take those differences into account in our fingerprinting study by conducting appropriate sieving. Further studies should focus on the variation of grain size of sediments during their transfer across catchments in order to outline the different erosion/transfer processes that are involved at different spatial and temporal scales.

496

# 497 **5** Conclusions

498 We can demonstrate from our core dating study that we could reconstruct the history 499 of sedimentation since Malijai dam building by analyzing and dating a sediment core 500 collected at this location, draining a 905-km<sup>2</sup> highly erosive Alpine catchment. Determination of 1963 bomb fallout peak is confirmed by the detection of <sup>241</sup>Am (emitted by the bombs but 501 502 not by Chernobyl accident). We could not detect any peak corresponding to Chernobyl fallout 503 in 1986 (which is confirmed by the very low rainfall amount observed in this catchment in 504 April – May 1986), but we could derive a mean sedimentation rate during this period, 505 providing a way to date the entire sediment core. The hydro-sedimentary interpretation 506 corroborates this analysis, and we could associate each major varve with very active erosive 507 periods that produced significant sediment exports since 1962 until 2009 at the Bléone River 508 outlet.

509 Black marls and (marly) limestones provided the bulk of sediment throughout the sequence 510 (on mean 40% and 22%, respectively) but we could outline the occurrence of major floods 511 generating huge quantities of sediment originating from Quaternary deposits and 512 conglomerates (on mean 25% and 16%, respectively). These results are consistent with the 513 ones obtained in previous studies where a similar sediment composition was found in 514 suspended sediment collected during (or after) large and widespread floods that occurred 515 between 2007 – 2009 in the Bléone River catchment. In contrast, those results slightly 516 differed with the ones derived from riverbed sediment analysis, outlining the need to take 517 account of the entire grain size range of sediment material within catchments to provide an 518 overall picture of sediment sources and transfers within highly erosive catchments.

519 Overall, this study also underlines the relevance of using archive data – i.e., hydrological 520 time-series and sediment core – to validate sediment fingerprinting analyses conducted 521 generally during short monitoring time-period (i.e., several years).

522

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652	Table and figure captions
653	Table 1         Summary of the meteorological and hydro-sedimentary data used in this study (SSC:
654	suspended sediment concentration; Q: discharge; R: rainfall). "R" and "STA" referred to as
655	the raingauges and hydrometric stations (Fig. 1)
656	
657	Fig. 1 Location of the study area in France, and location of the river monitoring stations
658	(STA1-STA7) and the raingauges (R1-R15) within the Bléone River catchment (Fig. A).
659	Location of the sediment coring site at the catchment outlet (Fig. B)
660	
661	Fig. 2 Geology of the Bléone River catchment and location of the river monitoring stations
662	(from Evrard et al. 2011)
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664	Fig. 3 Distribution of major floods (return period $> 1$ yr) recorded on the Bès River at Pérouré
665	station during the 1962-2009 period. Relation with the main hydro-meteorological events
666	(Fig. A). Seasonality of the major floods since 1962 (Fig. B). Regional variability of the
667	maximum annual specific discharge in the South-Eastern French Alps (Fig. C)
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669	Fig. 4 Sediment core dating derived from the distribution of 137Cs (Fig. A) and 210Pbxs (Bq
670	kg-1, Fig. B) activities with depth. Time-scale based on radionuclide dating (Fig. C)
671	
672	Fig. 5 Sediment core analysis and varve identification with X-ray intensity level (Fig. A, B).
673	Time-scale based on radionuclide dating (Fig. C)
674	
675	Fig. 6 Hydrometeorological data. Fig. A: monthly rainfall (in grey, the monthly data at the
676	different raingauges). Fig. B: maximum daily rainfall. Fig. C: discharge data of the Bès River
677	at Pérouré (daily and instantaneous discharge)
678	
679	Fig. 7 Core interpretation. Flash floods/debris flows and landslides frequency (RTM source;
680	Fig. A). Mean annual rainfall (moving average; Fig. B) and daily intensity rainfalls (moving
681	average; Fig. C). The "wet" years (black) and "dry" years (grey) are defined for each variable.
682	Varves' thickness (Fig. D). Time-scale based on radionuclide dating (Fig. E)
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684	Fig. 8 Sediment size composition (Fig. A) and sediment composition with geochemistry (Fig.
685	B). Time-scale based on radionuclide dating (Fig. C)

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- 687 Fig. 9 Total sediment yield (suspended sediment and bedload) at the Laval catchment
- 688
- 689 Fig. 10 Fine sediment origins at the Bléone River outlet. Proportion of draining catchment
- 690 surface occupied by the different lithologic sources (%, black bars), riverbed sediment
- 691 composition (%; white bars; Evrard et al. 2011), suspended sediment composition (grey bars;
- 692 mean  $\pm$  min./max. range of values obtained for the entire series of samples collected; Navratil
- 693 et al. 2012) and core composition (red bars; mean  $\pm$  min./max; this study)

**Fig. 1** Location of the study area in France, and location of the river monitoring stations (STA1–STA7) and the raingauges (R1–R15) within the Bléone River catchment (Fig. A). Location of the sediment coring site at the catchment outlet (Fig. B)



**Fig. 2** Geology of the Bléone River catchment and location of the river monitoring stations (from Evrard et al. 2011)



**Fig. 3** Distribution of major floods (return period > 1 yr) recorded on the Bès River at Péroure station during the 1962-2009 period. Relation with the main hydro-meteorological events (Fig. A). Seasonality of the major floods since 1962 (Fig. B). Regional variability of the maximum annual specific discharge in the South-Eastern French Alps (Fig. C)



**Fig. 4** Sediment core dating derived from the distribution of  $^{137}$ Cs (Fig. A) and  $^{210}$ Pb<sub>xs</sub> (Bq kg<sup>-1</sup>, Fig. B) activities with depth. Time-scale based on radionuclide dating (Fig. C)



Fig. 5 Sediment core analysis and varve identification with X-ray intensity level (Fig. A, B). Time-scale based on radionuclide dating (Fig. C)







**Fig. 7** Core interpretation. Flash floods/debris flows and landslides frequency (RTM source; Fig. A). Mean annual rainfall (moving average; Fig. B) and daily intensity rainfalls (moving average; Fig. C). The "wet" years (black) and "dry" years (grey) are defined for each variable. Varves' thickness (Fig. D). Time-scale based on radionuclide dating (Fig. E)



**Fig. 8** Sediment size composition (Fig. A) and sediment composition with geochemistry (Fig. B). Time-scale based on radionuclide dating (Fig. C)



Fig. 9 Total sediment yield (suspended sediment and bedload) at the Laval catchment



Fig. 10 Fine sediment origins at the Bléone River outlet. Proportion of draining catchment surface occupied by the different lithologic sources (%, black bars), riverbed sediment composition (%; white bars; Evrard et al. 2011), suspended sediment composition (grey bars; mean  $\pm$  min./max. range of values obtained for the entire series of samples collected; Navratil et al. 2012) and core composition (red bars; mean  $\pm$  min./max; this study)



Basin	Station	Drainage	Data type	Observation	Station manager
name	location	area (km²)		period	
Laval	Draix	0.86	Q, SSC (variable	1984-2010	Cemagref
			time step) STA8,		Grenoble/ETNA
			R6 to R10 (5. min.)		
Bès	Pérouré	165	Q, SSC (10. min.);	1962- 2010 for Q	SPC Grand Delta,
			STA3; STA4	2007-2010 for	DIREN, EDF-DTG,
				SSC	LTHE
Duyes	Mallemoisson	120	Q, SSC (10. min.)	2007-2010	LTHE
			STA 6		
Galabre	Roubine	22	Q, SSC (10. min.)	2007-2010	LTHE
			STA2		
Bléone	Prads	65	Q, SSC (10. min.)	2007-2010	LTHE
			STA5		
Bléone	Chaffaut	705	SSC (hourly)	2001-2003;	EDF-DTG
			STA1	2007-2010	
Bléone	Malijai	870	Q (hourly) ; STA7	2007-2010	EDF-DTG
Arigéole	Beaujeu		R (daily); R14	1926-2010	Météo France
Bléone	Digne		R (daily); R12	1945-2010	Météo France
Bès	Seyne		R(daily); R15	1928-2010	Météo France
Duyes	Thoard		R(daily); R13	1999-2010	Météo France
Bléone	Marcoux		R(hourly); R11	1938-2010	Météo France
Bès	Haut-Vernet		R (5 min.); R1	2008-2010	LTHE
Bès	Barles		R (5 min.); R2	2008-2010	LTHE
Galabre	Ainac		R (5 min.); R3	2008-2010	LTHE
Bléone	Serre		R (5 min.); R4	2008-2010	LTHE
Bléone	Les Dourbes		R (5 min.); R5	2008-2010	LTHE
Bès	Barles		R (5 min.); R2	2008-2010	LTHE

**Tab. 1** Summary of the meteorological and hydro-sedimentary data used in this study (SSC: suspended sediment concentration; Q: discharge; R: rainfall). "R" and "STA" referred to as the raingauges and hydrometric stations (Figure 1)

	Core depth																		
Section n°	(cm)	Mg	Al	Ti	Mn	V	Ni	Cu	Ag	Cd	Sb	Ba	TI	Pb	K (%)	Th-234	Ra-226	Ra-228	Th-228
1	5.4	9055	6.6	3647	463	103	50	24	0.16	0.16	0.39	376	0.54	13	1.70	31.1	22.0	32.8	35.0
2	13.4	8463	4.8	3550	582	88	38	20	0.21	0.18	0.36	349	0.38	12	1.59	28.8	22.5	30.6	30.9
3	18.7	10005	6.5	3422	458	102	45	19	0.15	0.14	0.29	273	0.47	13	1.79	26.4	23.0	34.3	32.2
4	27	9348	5.8	4230	680	104	44	20	0.17	0.13	0.34	305	0.43	13	1.55	30.0	23.0	31.6	32.0
5	33.2	6168	5.2	2688	393	81	40	23	0.21	0.14	0.32	446	0.38	12	1.29	24.3	22.0	29.0	27.1
6	45.7	8535	4.0	2917	705	70	39	21	0.19	0.14	0.36	266	0.29	14	1.28	23.9	20.0	28.1	25.9
7	49.7	10306	5.5	3192	568	83	45	20	0.20	3.25	0.42	244	0.37	53	1.27	23.0	20.0	28.4	26.3
8	56.9	8315	4.9	3473	689	88	42	23	0.22	0.14	0.61	359	0.38	13	1.44	30.0	24.0	28.0	30.0
9	65.5	10735	5.1	2929	455	86	43	18	0.15	0.14	0.39	232	0.38	13	1.40	23.9	22.5	28.7	28.6
10	70.8	8211	6.3	4221	580	114	46	26	0.24	0.19	0.54	446	0.53	13	1.63	25.2	26.0	32.4	31.0
11	74.5	8598	4.7	3173	739	82	41	19	0.25	0.14	0.42	259	0.36	13	1.49	19.4	22.5	29.0	28.9
12	84.0	9768	5.8	3210	579	92	44	20	0.27	0.13	0.40	267	0.40	14	1.37	21.0	20.0	28.9	27.8
13	100	9021	5.0	3925	815	94	43	19	0.23	0.14	0.37	292	0.36	13	1.37	21.9	20.0	28.2	28.3
14	109.1	10028	7.8	4842	681	135	44	18	0.45	0.14	0.79	323	0.58	13	1.62	28.5	23.0	35.0	31.1
15	116.4	7221	3.6	1868	489	59	37	18	0.16	0.13	0.39	262	0.26	14	0.88	13.1	19.0	18.6	16.9
16	117.6	7740	3.1	2553	677	59	34	19	0.22	0.15	0.44	254	0.25	12	0.88	13.1	16.0	18.6	16.9
17	123.6	8312	5.1	3795	610	98	41	19	0.29	0.17	0.41	332	0.39	12	2.02	26.3	24.0	33.0	35.7
18	133.0	9406	6.5	3366	433	101	44	19	0.26	0.13	0.36	342	0.47	13	1.63	27.3	21.0	32.4	30.4
19	139.5	8063	4.3	3183	623	80	35	19	0.16	0.17	0.35	315	0.36	12	1.14	22.3	20.0	25.7	22.6
20	142	7579	3.3	2707	628	65	31	17	0.14	0.16	0.29	301	0.28	10	1.13	18.5	18.5	21.1	21.5
21	150.0	7270	3.1	1654	457	48	32	16	0.12	0.11	0.41	256	0.23	12	0.84	16.2	17.0	17.2	17.1
22	157.5	7889	2.8	2349	666	53	34	19	0.17	0.14	0.38	268	0.23	12	0.97	16.7	17.0	21.1	19.5
23	169.5	6995	3.0	1642	471	43	34	17	0.15	0.12	0.44	258	0.22	12	0.87	11.9	17.0	18.7	18.5
24	198.0	9490	4.3	2384	509	78	40	24	0.15	0.13	0.40	268	0.31	15	1.20	21.9	21.0	25.0	24.1
25	207.5	8381	4.2	2676	615	70	33	18	0.23	0.13	0.33	289	0.33	12	1.10	18.4	17.0	18.0	19.2
26	223.0	5620	2.0	914	430	27	26	10	0.04	0.10	0.25	170	0.16	9	0.67	10.4	13.0	11.9	10.8
27	231	7831	3.1	2843	711	66	36	20	0.16	0.17	0.54	246	0.28	15	0.92	13.1	15.0	17.5	16.0
28	241.0	8335	4.1	2282	483	72	39	19	0.15	0.13	0.36	261	0.30	14	1.11	23.8	20.0	24.4	23.9
29	247	9186	4.5	2988	610	72	33	17	0.19	0.14	0.37	286	0.31	11	1.23	23.4	20.5	24.0	24.4
30	255.5	8797	6.1	4093	670	114	47	21	0.21	0.17	0.38	366	0.50	13	1.47	24.5	21.0	27.9	27.3
31	260.0	9712	5.4	2918	523	93	43	19	0.14	0.18	0.36	290	0.39	14	1.59	23.9	23.0	30.6	29.9
32	275.3	10269	6.2	3292	524	98	48	23	0.12	0.18	0.38	382	0.49	15	1.72	27.2	29.0	30.2	31.0
33	280.8	9916	6.2	3818	620	110	42	18	0.21	0.14	0.47	366	0.59	12	1.81	20.1	23.0	31.8	30.5
34	286	12017	6.1	3743	500	105	40	15	0.22	0.13	0.50	307	0.57	12	2.07	30.4	23.0	36.1	36.7

**Tab. 2** Concentrations in geochemical elements (mg kg<sup>-1</sup>) and mean radionuclide activities (in Bq kg<sup>-1</sup>, except for K – in %) analysed in the sediment core sections (n=34)