



HAL
open science

Linking Danube River activity to Alpine Ice-Sheet fluctuations during the last glacial (ca. 33–17 ka BP): Insights into the continental signature of Heinrich Stadials

Ruth Martinez-Lamas, Samuel S. Toucanne, Maxime Debret, Vincent Riboulot, Julien Deloffre, Audrey Boissier, Sandrine Chéron, Mathilde Pitel, Germain Bayon, Liviu Giosan, et al.

► To cite this version:

Ruth Martinez-Lamas, Samuel S. Toucanne, Maxime Debret, Vincent Riboulot, Julien Deloffre, et al.. Linking Danube River activity to Alpine Ice-Sheet fluctuations during the last glacial (ca. 33–17 ka BP): Insights into the continental signature of Heinrich Stadials. *Quaternary Science Reviews*, 2020, 229, pp.106136. 10.1016/j.quascirev.2019.106136 . hal-02548932

HAL Id: hal-02548932

<https://normandie-univ.hal.science/hal-02548932v1>

Submitted on 21 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Linking Danube River Activity to Alpine Ice-Sheet Fluctuations during the**
2 **Last Glacial (*ca.* 33-17 ka BP): insights into the continental signature of**
3 **Heinrich Stadials**

4

5 Ruth Martinez-Lamas^{a,b,*}, Samuel Toucanne^b, Maxime Debret^a, Vincent Riboulot^b, Julien
6 Deloffre^a, Audrey Boissier^b, Sandrine Cheron^b, Mathilde Pitel^b, Germain Bayon^b, Liviu
7 Giosan^c & Guillaume Soulet^b

8

9

10 ^a Normandie Univ., UNIROUEN, UNICAEN, CNRS, M2C, F-76000, Rouen, France

11 ^b IFREMER, Unité de Recherche Géosciences Marines, F-29280, Plouzané, France

12 ^c Department of Geology and Geophysics, Woods Hole Oceanographic Institution, 266
13 Woods Hole Road, Woods Hole, MA 02543, USA

14

15

16 * Corresponding author. E-mail address: *ruth.martinez-lamas1@univ-rouen.fr* (R. Martinez-
17 Lamas), *stoucann@ifremer* (S. Toucanne)

18 **ABSTRACT**

19

20 Offshore archives retrieved from marine/lacustrine environments receiving sediment from
21 large river systems are valuable Quaternary continental records. In the present study, we
22 reconstruct the Danube River activity at the end of the last glacial period based on
23 sedimentological, mineralogical and geochemical analyses performed on long-piston cores
24 from the north-west Black Sea margin. Our data suggest that the Danube River produced
25 hyperpycnal floods throughout the *ca.* 33-17 ka period. Four main periods of enhanced
26 Danube flood frequency, each of 1.5-3 kyr duration, are recorded at *ca.* 32.5-30.5 ka
27 (equivalent to the first part of Heinrich Stadial -HS- 3), at *ca.* 29-27.5 ka (equivalent to
28 Greenland Stadial 4), at *ca.* 25.3-23.8 ka (equivalent to HS 2) and at *ca.* 22.3-19 ka. Based on
29 mineralogical and geochemical data, we relate these events to enhanced surface melting of the
30 Alpine Ice Sheet (AIS) that covered ~50,000 km² of the Danube watershed at the Last Glacial
31 Maximum (LGM). Our results suggest that (i) the AIS growth from the inner Alps to its LGM
32 position in the northern Alpine foreland started from *ca.* 30.5 ka, ended no later than
33 *ca.* 25.3 ka, and was interrupted by a melting episode *ca.* 29-27.5 ka; (ii) the AIS volume
34 drastically decreased from *ca.* 22.3 to 19 ka, as soon as summer insolation energy at the AIS
35 latitude increased; and (iii) HSs strongly impacted the AIS mass balance through enhanced
36 summer surface melt. This, together with evidence of severely cool winters and the rapid
37 expansion of sea ice in the North Atlantic, implies strong seasonality in continental Europe
38 during stadials.

39

40 Keywords: Danube River, floods, hyperpycnites, Alpine Ice Sheet, Heinrich Stadials,
41 seasonality, Black Sea.

42 1. INTRODUCTION

43

44 Fluvial landforms and sediments can be used to reconstruct past hydrological conditions since
45 rivers are highly sensitive to environmental changes (Blum and Törnqvist, 2000; Macklin et
46 al., 2012). Prominent examples from the British Isles (Macklin et al., 2005; Macklin and
47 Lewin, 2003) and continental Europe (Busschers et al., 2007; Gábris and Nádor, 2007;
48 Gibbard, 1988; Kasse et al., 2010; Macklin et al., 2006; Mol et al., 2000; Pastre et al., 2003;
49 Starkel et al., 2015; Vandenberghe, 2002) point to the impact of Quaternary climate change
50 on river system dynamics. However, the riverine archives are highly complex (*e.g.* spatially-
51 dependant types and rates of sedimentation, hiatus and erosion, difficulties in dating; Blum
52 and Törnqvist, 2000; Coulthard et al., 2005; Macklin and Lewin, 2003; Vandenberghe, 2003).
53 Hence the use of sediment archives retrieved offshore of large river systems can provide
54 complementary high-frequency sediment flux records resulting from river discharge and
55 climate variability (Simpson and Castellort, 2012). This has been demonstrated in various
56 geographic and climatic settings (*e.g.* Bonneau et al., 2014; Covault et al., 2011; Goodbred
57 and Kuehl, 2000; Revel et al., 2010), including the giant glaciated catchments of European
58 rivers, *i.e.* the Channel River (Ménot et al., 2006; Toucanne et al., 2009; Zaragosi et al., 2001)
59 and the Dniepr River (Soulet et al., 2013). These studies provided remarkable new insights
60 into the paleohydrology of Europe during past glacial intervals as well as into the impact of
61 the Fennoscandian Ice Sheet (FIS) in amplifying, pacing and driving regional and global
62 climate changes (*e.g.* Boswell et al., 2019; Soulet et al., 2013; Toucanne et al., 2015).

63 It is well-known that the Black Sea received vast amounts of sediment and meltwater from the
64 Alpine Ice Sheet (AIS) and FIS during glacial periods (Bahr et al., 2006; Gorlach et al., 2017;
65 Grosswald, 1980; Major et al., 2006; Mangerud et al., 2004; Soulet et al., 2013, 2011a;
66 Tudryn et al., 2016). The Red Layers (*e.g.* Bahr et al., 2006), deposited in the north-west
67 Black Sea by the Dniepr River and the retreating FIS between *ca.* 17.2 and 15.7 ± 0.3 cal ka
68 BP (Soulet et al., 2013), constitute a prominent example further highlighting the ability for
69 ice-sheets to impact sediment routing systems down to the deep sea 'sink' (Jaeger and
70 Koppes, 2016). By comparison, the impact of AIS fluctuation on the Danube River discharge
71 and Black Sea sedimentary system has received much less attention. Yet, the entire north-east
72 part of the AIS (~50,000 km²) drained into the Black Sea and sediment accumulated in the
73 Danube delta (Giosan et al., 2006, 2005; Panin et al., 1983) and deep-sea fan (Constantinescu
74 et al., 2015; Lericolais et al., 2013; Popescu et al., 2001; Wong et al., 1994) must have
75 recorded Danube River activity and AIS fluctuations during the late Quaternary. Here, we

76 provide a continuous, high-resolution record of the Danube River discharge into the Black
77 Sea ‘Lake’ at the end of the last glacial period (from *ca.* 33.5 ka) through the study of two
78 sediment cores retrieved midway between the Danube delta and the Danube deep-sea fan
79 (Fig. 1). Millennial-scale variability in sediment input and source observed in our multi-proxy
80 records suggests rapid regional-scale glacier fluctuations in the north-eastern Alps over the
81 course of the AIS to its maximum extent and during the deglaciation.

82

83 **2. GEOLOGICAL AND ENVIRONMENTAL SETTINGS**

84

85 **2.1 The north-west Black Sea and the Danube sediment routing system**

86 Since its opening during the Upper Cretaceous, the Black Sea basin acts as a large sediment
87 catchment area that accumulated a thick sedimentary cover of ~19 km in its western margin.
88 Since the Pliocene, a 2.5 to 3 km-thick prograding depositional wedge has been formed by
89 Danube and Dniepr sedimentary supplies (de Leeuw et al., 2018; Nikishin et al., 2003). This
90 geological feature, forming the wide north-west Black Sea continental shelf (<140-170 m
91 water depth) and margin, is incised by numerous erosive canyons (Riboulot et al., 2017)
92 including the Danube Canyon which deeply incises the shelf over 26 km down to -110 m
93 water depth (Popescu et al., 2004) (Figs 1 and 2). The Danube Canyon has fed an extensive,
94 deep depositional (turbidite) system (*i.e.* Danube deep-sea fan) at water depths greater than
95 2000 m (Lericolais et al., 2013; Popescu et al., 2001; Wong et al., 1994). It has been active
96 during the last glacial period and until *ca.* 11.7 ka (Constantinescu et al., 2015) when the
97 Black Sea was a giant freshwater lake and lowstand conditions (~90-120 m below the present
98 sea level) dominated (Deuser, 1972; Lericolais et al., 2011; Ross et al., 1970; Ryan et al.,
99 1997; Yanchilina et al., 2017). The Danube deep-sea fan thus represents the final sink of the
100 Danube sediment routing system (Matenco and Andriessen, 2013) (Fig. 1), *i.e.* the integrated
101 dynamical system connecting erosion in mountain catchments of western Central Europe to
102 downstream deposition in the Black Sea.

103 The Danube River is the second longest river in Eurasia, with a length of 2,900 km from the
104 Black Forest (Germany) to its delta (Romania) (Fig. 1), a drainage area of 801,000 km² and a
105 modern sediment load estimated at 42-67 Mt per year (sediment yield: ~80 t.km².yr⁻¹). Today,
106 it constitutes by far the main sediment source for the northern Black Sea considering the low
107 sediment load, estimated to be less than 10 Mt per year in total, for the rivers Dniestr
108 (sediment yield: ~30 t.km².yr⁻¹), Dniepr and Don (sediment yield: ≤5 t.km².yr⁻¹). This
109 difference is due to the mountainous character of the Danube drainage area in comparison to

110 the lowlands-dominated Dniestr, Dniepr and Don watersheds (Milliman and Farnsworth,
111 2013; Milliman and Syvitski, 1992; Panin and Jipa, 2002; Sommerwerk, 2009). Indeed, the
112 Danube River collects water and sediment from the mountainous areas of the northern and
113 eastern Alps (up to 4,049 m high at Piz Bernina; Fig. 3), the Dinarides and the Carpathians
114 (Fig. 1), mainly formed of Variscan metamorphic and magmatic basements and Mesozoic
115 calcareous rocks (Asch et al., 2005). In detail, from its source to its mouth, the Danube River
116 receives the following: on its right bank, the tributaries Iller, Inn, Enns, Drava and Sava,
117 originating in the Alps and the Dinarides, as well as the Velika Morava flowing from the
118 Balkans; and on its left bank, the major tributaries Morava, rising in the Bohemian Forest, and
119 Tisza, originating in the Carpathians, and the Jiu, Olt, Siret and Prut rivers, with sources in the
120 Carpathians (Garnier et al., 2002) (Fig. 1). In addition to the riverine material from the
121 mountainous areas, the glacial loess deposits constitute a significant additional sediment
122 supply to the Danube sediment load, especially in the Pannonian (Middle Danube) and Dacic
123 (Lower Danube) basins (Marković et al., 2015).

124

125 **2.2 Paleoenvironmental changes in the Danube drainage area**

126 The loess and glacial sequences preserved in the Danube catchment provide information
127 on the intensity of Alpine glaciations (Marković et al., 2015), with the first major glaciation in
128 the Alps dating from Marine Isotope Stage (MIS) 22 (Muttoni et al., 2003). The (local) Last
129 Glacial Maximum (LGM) in the Alps (Upper Würmian, MIS 2; Chaline and Jerz, 1984,
130 Figs 1 and 3) lasted from not later than *ca.* 24 to 20-19 ka (*e.g.* Ivy-Ochs, 2015; Ivy-Ochs et
131 al., 2008; Monegato et al., 2017), with glaciers extending tens of kilometers out onto
132 forelands and coalescing into huge (Rhine, Isar/Loisach, Inn, Salzach and Traun, from west to
133 east) piedmont lobes (up to 700 m in thickness) in the Molasse Basin, Upper Danube (Ivy-
134 Ochs, 2015; van Husen, 2000) (Fig. 3). This time period is coeval with peak loess
135 accumulation rates in the Pannonian Basin (Fitzsimmons et al., 2012) and the development of
136 the Duttendorf loess sequence in the Salzach palaeoglacier area (Starnberger et al., 2011).
137 Recent compilation of ¹⁰Be surface exposure dating and radiocarbon ages demonstrate that if
138 LGM glaciers vanished rapidly from the foreland at *ca.* 20-18 ka, the initiation of retreat from
139 their maximum positions occurred as soon as *ca.* 24-22 ka (Ivy-Ochs, 2015; Ivy-Ochs et al.,
140 2004; Reber et al., 2014). Note that the timing for the growth and demise of cirque and
141 cirque-valley glaciers in the western and southern Carpathians mountains matches that
142 recognized in the northern Alps (Makos et al., 2018, 2014, 2013; Reuther et al., 2007).

143 In contrast, little is known about pre-LGM ice fluctuations (Ivy-Ochs et al., 2008). The
144 Middle Würmian (MIS 4 and 3; Chaline and Jerz, 1984) is poorly preserved in the Alps due to
145 the excavation of valleys by the LGM ice advance soon after *ca.* 33-32 ka (*i.e.* onset of the
146 Upper Würmian, as redefined by Spötl et al., 2013). However, recent ¹⁰Be data from the
147 western Alps and the Rivoli-Avigliana end-moraine system (northern Italy) yield a minimum
148 age of 41.2 ± 1.9 ka (MIS 3) for pre-LGM glacier advance(s) in the Pô Valley (Ivy-Ochs et
149 al., 2018). This age fits well with the deterioration of climatic conditions over the Alps after
150 *ca.* 45 ka (Heiri et al., 2014; Starnberger et al., 2013). These results, including recent ones
151 from the Berchtesgaden basin (Germany; Mayr et al., 2019), corroborate numerical
152 simulations suggesting that a highly dynamic ice-sheet occupied the inner-Alpine regions
153 throughout the last glacial period, with possible recurrent short-lived advances onto the
154 forelands well before the LGM (Seguinot et al., 2018).

155

156 **3. MATERIALS**

157

158 **3.1. Sediment cores**

159 This study focuses on the Calypso long-piston cores GAS-CS01 (44°05.1'N, 30°47.5'E) and
160 MD04-2790 (44°12.8'N, 30°59.6'E) retrieved from the north-west Black Sea margin (**Figs 1**
161 **and 2; Table 1**). Core GAS-CS01 (33.4 m long) was collected at 240 m water depth from the
162 shelf margin, ~40 km east of the Danube Canyon head, during the GHASS oceanographic
163 cruise (R/V Pourquoi Pas?; Ker and Riboulot, 2015). Core MD04-2790 (30.3 m long) is
164 located at 352 m water depth, ~19.6 km east of GAS-CS01. This core was collected during
165 the ASSEMBLAGE-1 cruise (R/V Marion Dufresne; Lericolais, 2004) and has been
166 extensively studied over the last few years for chronostratigraphical and paleoenvironmental
167 studies (*e.g.* Soulet et al., 2011a,b; Sanchi et al., 2014). Note that the length of cores GAS-
168 CS01 (this study) and MD04-2790 (Soulet et al., 2011a) has been corrected after removal of
169 coring gaps (corrected length of 32.1 and 27.8 m, respectively). Core depths discussed in this
170 study thus correspond to depth (cm, m) below sea floor (bsf), and corresponding depths (raw -
171 cm- versus -cmbsf-) are presented in **Tables 2 and 3**.

172

173 **3.2. Danube River and tributary samples**

174 In order to track paleoenvironmental changes in the Danube sediment routing system,
175 eighteen riverine sediments have been recovered from the Danube River and its tributaries to
176 compare their mineralogy with that of the GAS-CS01 core samples (**Fig. 1; Table 3**). Fine-

177 grained river sediments constitute the mineralogical diversity of catchment areas. As such
178 they can provide a reliable average mineralogical and geochemical composition of their
179 corresponding drainage basin (Chamley, 1989; Sionneau et al., 2008). Considering the
180 disproportionate role of mountains and glaciers in the erosion processes and the river
181 sediment yields (Hallet et al., 1996; Milliman and Syvitski, 1992; Comiti et al., 2019), we
182 mainly collected river sediments from tributaries draining the northern Alps (*e.g.* Iller, Inn;
183 $n=5$), the western Carpathians (*e.g.* Tisza, Morava; $n=5$) and the Dinarides (Sava and Velika
184 Morava rivers; $n=2$). Additional samples were collected along the Danube mainstream ($n=6$)
185 from Passau (Germany) to the Black Sea, near the confluence with the Tisza and Velika
186 Morava rivers. At every location where fine sediment was available, samples were collected
187 from fresh bank deposit.

188

189 **4. METHODS**

190

191 **4.1 Core-scale analyses**

192 The sedimentological analysis of GAS-CS01 is firstly based on visual description and X-ray
193 images that allow the recognition of the main sedimentary facies and sequences, and the
194 manual counting of laminae/beds (see Part 6.1; Fig. 4). 2D X-ray images were acquired with a
195 Geotek XCT system (Ifremer, Brest) from split core sections. Detailed identification of the
196 sedimentary facies was completed by hyperspectral reconstructed images. The hyperspectral
197 spectroscopy technique consists of combining reflectance spectroscopy and digital imaging. A
198 high-resolution digital image of a sediment core and a reflectance measurement for a specified
199 wavelength range are collected in each pixel of the digital image. The wavelength intervals at
200 which absorption features appear in their reflectance spectra are determined by the chemical
201 compounds (*e.g.* organic matter) and physical properties (*e.g.* grain size) of the sediments
202 (Debret et al., 2018; Jacq et al., 2019; Van Exem et al., 2019). In this study, we present high-
203 resolution reconstructed images (spatial resolution of $\sim 61 \mu\text{m}/\text{pixel}$) in order to highlight the
204 sedimentary features in GAS-CS01. Hyperspectral images were acquired at the University of
205 Rouen (France) using a Specim (Spectral Imaging Ltd.) sediment-core-scanning system in
206 combinations with a Specim PFD-xx-V10E camera (Specim Ltd., Finland) and OLES22.5
207 lens. These high-resolution images were acquired in the VNIR (Visible and Near InfraRed)
208 spectral range between 400 to 1000 nm. The colour obtained with the VNIR is a false
209 (highlighted) colour constructed after selecting three bands in the RGB system (697.94,
210 548.87 and 469.59 nm).

211 The bulk intensity of major elements for core GAS-CS01 was analysed using an Avaatech
212 XRF core-scanner (Ifremer, Brest). XRF data were collected every 1 cm along the entire core,
213 with a count time of 10 s, by setting the voltage to 10 kV (no filter) and 30 kV (Pd thick filter)
214 and the intensity to 600 mA and 1000 mA, respectively. Millimetre-scale analyses were also
215 conducted on some sections (30 s., 10-30 kV, 1000 mA) (Fig. 5).

216 The global mineralogy composition of GAS-CS01 sediments was determined by X-ray
217 diffractometry (XRD), using a D8 Advance BRUKER model, a device type Bragg-Brentano
218 equipped with a Cu X-ray tube, a primary Soller slit of 0.6 mm, a nine-position sample holder
219 and the VANTEC-1 Position Sensitive Detector with a nickel filter (Ni 0.5). Prior to analysis,
220 dried sediment powders were inserted into the sample holder, and flattened. Measurements
221 were made from 5 to 70° with a resolution of 0.01° lasting 1 s. The voltage and amperage
222 were set up to 40 kV and 30 mA, respectively.

223 The clay mineralogy composition of GAS-CS01 sediments was determined by X-ray
224 diffractometry (XRD), using a D2 PHASER BRUKER model, a Bragg-Brentano device type
225 equipped with a Cu X-ray tube, a primary Soller slit of 0.6 mm and the LYNXEYE Detector
226 with a nickel filter (Ni 0.5). In order to separate the clays from the rest of the matrix, the
227 sample undergoes several stages of preparation: various chemical treatments to eliminate
228 carbonates, iron oxides as well as the organic matter and a settling. Finally, these clays are
229 plated on an oriented glass slide which is analysed in three different ways: without treatment,
230 after saturation with ethylene glycol and after calcination at 490°C. Measurements were made
231 from 2 to 30° with a resolution of 0.02° lasting 1 s. The voltage and amperage were set to
232 30 kV and 10 mA, respectively. The illite crystallinity (ICr) index, or Kübler index (Kisch,
233 1991), was measured from XRD results. The illite crystallinity ($^{\circ}\Delta 2\theta$) is the full width at half
234 maximum (FWHM) determined from the illite peak at 10 Å (Chamley, 1989). The clay
235 mineralogy and the ICr of the riverine samples ($n=18$) were also determined.

236 Finally, the geographical provenance of the GAS-CS01 sediments was determined measuring
237 Nd isotopic ratios of fine-grained detrital fraction ($n=14$). The neodymium isotopic
238 composition (ϵ_{Nd}) of terrigenous sediment is a powerful tracer for geographical provenance
239 because the ϵ_{Nd} signature of detrital sediment is retained during continental weathering and
240 subsequent transport (Bayon et al., 2015; Goldstein and Jacobsen, 1988). We focus on the
241 <63 µm fraction because the meltwaters of ice margins predominantly transport the clay and
242 silt fractions of continental detritus (Boswell et al., 2018; Brown and Kennett, 1998). All bulk
243 samples were first treated to quantitatively remove any biogenic, authigenic and organic
244 compounds (Bayon et al., 2002) and residual detrital fractions were digested by alkaline

245 fusion prior to isolation of the Nd by ion-exchange chromatography (Bayon et al., 2009). Nd
246 isotope measurements were performed on a Thermo Scientific Neptune MC-ICP-MS at the
247 Pôle Spectrométrie Océan, Brest (France). Mass bias corrections on Nd were made with the
248 exponential law, using $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Nd isotopic compositions were determined
249 using sample-standard bracketing, by analysing an internal standard solution every two
250 samples. Mass-bias corrected values for $^{143}\text{Nd}/^{144}\text{Nd}$ were normalized to a JNdi-1 value.
251 Replicate analyses of the JNdi-1 standard solution during the course of this study gave
252 $^{143}\text{Nd}/^{144}\text{Nd} = 0.512113 \pm 0.000013$ (2SD, $n=28$), in full agreement with the reference value
253 (0.512115) of Tanaka et al. (2000), and corresponding to an external reproducibility of \sim
254 ± 0.25 ϵ -units, taken as the estimated uncertainty on our measurements. In this study, both
255 measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios and literature data are reported in ϵ_{Nd} notation
256 $[(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}} / (^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} - 1] \times 10^4$, using $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$
257 (Jacobsen and Wasserburg, 1980). The ϵ_{Nd} dataset available in core MD04-2790 for the
258 *ca.* 28-10 ka period (Soulet et al., 2013) was produced using this procedure.

259

260 **4.2 Laminae-scale analyses**

261 To characterize the sedimentary facies of core GAS-CS01, and the laminations in particular
262 (see Part 6.1), we performed microscopic observations of 8 cm long thin-sections of
263 impregnated sediments. The thin sections were prepared at the Université de Bordeaux (UMR
264 EPOC) according to the protocol described in Zaragosi et al. (2006). The studied intervals
265 were selected from well-preserved and representative sedimentary facies (Fig. 4). The thin
266 sections were then used for geochemical characterization of the sediments via scanning
267 electron microscopy (SEM) at Ifremer, using a Thermo Scientific Quanta 200 equipped with
268 an OXFORD Instrument X-MAXN silicon drift detector energy-dispersive X-Ray
269 spectrometer (detector size: 80 mm²). The thin sections were coated with a thin layer of
270 carbon and X-ray EDS maps acquired on an area of about 300 mm² to investigate the
271 microscale geochemical distribution/composition of the sediments. Each area is composed of
272 over 30 fields (3.47 × 3.04 mm each) scanned with a resolution of 1024 × 896 pixels (1 pixel
273 = 3.4 μm). Additionally, morphological analyses of lithic grains were performed through
274 SEM (Quanta 200). The grains were deposited onto SEM sample holders covered with a gold
275 layer, and the SEM images were obtained with the secondary electron detector mode and an
276 accelerating voltage of 5.0 kV.

277 Finally, we performed a total of 398 grain-size analyses using a Malvern Mastersizer 3000
278 laser diffraction particle size analyser (0.1-2000 μm) coupled with a Hydro LV wet dispersant

279 unit. Ultrasonic dispersion (2 minutes) was conducted before analysis. The average resolution
280 is 0.25 cm along the studied intervals.

281

282 **5. AGE-DEPTH MODEL**

283

284 Core chronologies based on radiocarbon dates are hampered in the Black Sea by
285 unconstrained reservoir age (Guichard et al., 1993; Jones and Gagnon, 1994; Kwiecien et al.,
286 2008; Soulet et al., 2011a, 2019). To circumvent the reservoir age issue, it is possible to
287 reconstruct a meaningful environmental proxy from the core sediment and align it to a
288 calendrically-dated reference record (*e.g.* Bard et al., 2004, 2013; Heaton et al., 2013; Skinner
289 et al., 2010, 2020; Soulet et al., 2011a) in order to obtain the calendar age-depth model
290 without using radiocarbon dates. Original calendar age-depth model of core MD04-2790 is
291 based on the alignment approach (Soulet et al., 2011a): TEX86-derived Lake Surface
292 Temperature (LST) reconstructed from MD04-2790 sediments was aligned to Hulu Cave $\delta^{18}\text{O}$
293 speleothem record (Wang et al., 2001). The GAS-CS01 calendar age-depth model is based on
294 that of core MD04-2790, through the alignment of their respective XRF-Ca records (**Fig. 5**)
295 which provided calendar ages at tie-points. The striking resemblance of XRF-Ca records
296 confirms that the XRF Ca_{norm} is a basin-wide stratigraphic proxy in the Black Sea (Bahr et al.,
297 2005, 2008; Kwiecien et al., 2008; Soulet et al., 2011a; Constantinescu et al., 2015). Original
298 MD04-2790 age-depth model was performed until to the depth 1990 cmbsf (31.3 ka),
299 corresponding to depth 1595 cmbsf in core GAS-CS01. Below, MD04-2790 LST record did
300 not provide reliable tie-point compared to Hulu Cave record (Soulet et al., 2011a). Hence,
301 below the depth 1990 cmbsf in MD04-2790 and the depth 1595 cmbsf in GAS-CS01, the
302 chronology is based on radiocarbon dates (*Dreissena* sp. and bulk organic matter; **Table 2**).
303 We implemented these chronological constraints (**Supplementary Table S1 and S2**) in Oxcal
304 (Bronk Ramsey, 2001, 2008, 2009; Bronk Ramsey and Lee, 2013; Bronk Ramsey, 2017). As
305 reservoir ages are unconstrained for this period, we applied a vague reservoir age correction
306 following a uniform distribution spanning 0 to 5000 ^{14}C yrs correction. Oxcal codes and
307 further details of the modelled age-depth models are available in Supplementary Online
308 Material. We found that the base of both cores consistently dates back to ~33.5 ka
309 (**Supplementary Figs. S1 and S2**).

310

311 **6. RESULTS**

312

313 **6.1 GAS-CS01 lithology**

314 The analysis of core GAS-CS01 shows the the classic regional lithological succession
315 consisting of the microlaminated coccolith ooze (MCO; 0-0.04 mbsf), the black-brown micro-
316 laminated sapropel (0.04-0.52 mbsf), and the carbonate-rich layers (down to 2.53 mbsf)
317 overlying the Red Layers (2.53-4.26 mbsf). Below the Red Layers down to the bottom
318 (32.1 mbsf), the GAS-CS01 lithology consists of even, parallel clastic rythmites. This
319 lithological succession, found from the north-west Black Sea upper slope (Bahr et al., 2005;
320 Major et al., 2002; Soulet et al., 2011a) to the Danube deep-sea fan (Constantinescu et al.,
321 2015), corresponds to ‘marine’ Unit I (MCO, $<2,720 \pm 160$ cal a BP) and Unit II (sapropel,
322 deposited from $8,080 \pm 250$ cal a BP) and below, ‘lacustrine’ Unit III (glacial ‘banded lutites’)
323 described by Ross and Degens (1974). Consequently, the carbonate-rich silty clay is
324 interpreted as the upper part of the ‘lacustrine’ Unit III (Dean and Arthur, 2011). This
325 sediment deposited during the late glacial (including the Bølling-Allerød Interstadial and the
326 Younger Dryas cold event), from 15.7 ± 0.3 cal ka BP (upper part of the Red Layers; Soulet et
327 al., 2011a) and the Initial Marine Inflow *ca.* 9 ka (Soulet et al., 2011b). Based on the above,
328 core GAS-CS01 therefore consists of a very high-resolution record of the glacial (*sensu*
329 *stricto*, > 16 ka) ‘lacustrine’ Unit III (until *ca.* 33.5 ka; see Part 5 ‘Age-depth model’).

330 In detail, the glacial sequence of GAS-CS01 is fully laminated (total of 3815 laminae/beds
331 revealed by X-ray imagery) and consists of even, parallel clastic rythmites that resemble the
332 varve pattern of Degens et al. (1978). They consist of silty to sandy graded deposits, evolving
333 gradually from millimetre- (*i.e.* laminae; Scandinavian-type lacustrine varves of Degens et al.,
334 1978) to decimetre-thick deposits (*i.e.* beds; megavarves of Degens et al., 1978) from the Red
335 Layers (2.53-4.26 mbsf) to the core bottom (32.1 mbsf) (Figs 4 and 6). They are separated by
336 muddy intervals of similar thickness (*i.e.* mm- to dm-thick from top to bottom). Interestingly,
337 the grain-size of the deposits is positively correlated with the thickness of the clastic intervals,
338 from silt-sized grains in the Red Layers to sand-sized particles in the deeper part of GAS-
339 CS01. High-resolution grain-size analyses reveal the superposition of (basal) coarsening-up
340 and (top) fining-up sequences throughout GAS-CS01. This pattern is mirrored by the
341 millimetre-scale XRF Zr/Rb, well-known as a semi-quantitative grain-size indicator (Dypvik
342 and Harris, 2001) (Figs 7, 8 and 9). All these results (and the inversely graded facies in
343 particular) suggest that the clastic rythmites in GAS-CS01 are hyperpycnite sequences, *i.e.*
344 deposits that are related to quasi-steady hyperpycnal (*i.e.* ‘above a density threshold’)
345 turbidity currents (Mulder et al., 2003; Mulder and Alexander, 2001). The detailed
346 observation of X-ray images and thin-sections reveal similar sedimentary deposits (including

347 4841 laminae) at site MD04-2790 (Soulet et al., 2011a), ~20 km east of GAS-CS01. This
348 highlights the regional imprint of hyperpycnal flows in the north-west Black Sea 'Lake'
349 during the last glacial period.

350

351 **6.2 Hyperpycnal turbidites frequency**

352 The frequency of hyperpycnal turbidite deposits (hyp.250 yr^{-1}) has been estimated for cores
353 GAS-CS01 and MD04-2790 (Fig. 10b and Supplementary Online Material). The two cores
354 present similar trends. A peak in hyperpycnal turbidite frequency ($>100 \text{ hyp.250 yr}^{-1}$) is
355 observed from *ca.* 32.5-30.5 ka with a maximum (up to $380 \text{ hyp.250 yr}^{-1}$ at GAS-CS01)
356 estimated at *ca.* 31 ka. A rapid decrease is observed thereafter ($<50 \text{ hyp.250 yr}^{-1}$), followed by
357 a new increase centred at 29-27.5 ka ($\sim 150 \text{ hyp.250 yr}^{-1}$ at MD04-2790). Then, a ~10-kyr-
358 long period (from *ca.* 27 to 17 ka) of moderate hyperpycnal turbidite frequency fluctuating
359 between ~15 and $50 \text{ hyp.250 yr}^{-1}$ is observed. During this interval, two main episodes of
360 increasing frequency (up to $\sim 50\text{-}70 \text{ hyp.250 yr}^{-1}$) are observed, at *ca.* 25.3-23.8 ka and at
361 *ca.* 22.3-19 ka. A last peak in hyperpycnal turbidite frequency is observed at the two sites
362 at 17.2- 16 ka, *i.e.* during the deposition of the Red Layers. The evolution of sediment
363 accumulation rates calculated for the two cores strictly follows that of the hyperpycnal
364 turbidite frequency (Fig. 10c).

365

366 **6.3 Sedimentary geochemistry**

367

368 **6.3.1 Clay mineralogy**

369 The GAS-CS01 clay mineralogy ($n=146$; Fig. 10d,e and Supplementary Online Material)
370 reveals the dominance of both smectite ($39 \pm 13\%$) and illite ($36 \pm 10\%$) over chlorite
371 ($15 \pm 7\%$) and kaolinite ($11 \pm 5\%$). From *ca.* 31 to 17.2 ka, the abundance of clay minerals
372 fluctuates (up to ~15-20% variability for smectite) but is relatively stable in comparison to the
373 >31 ka (peak in hyperpycnal turbidite frequency; see Part 6.2) and <17.2 ka (Red Layers)
374 intervals. Indeed, the oldest interval of GAS-CS01 is characterised by high abundances in
375 illite (~40-45%) and chlorite (~20-30%), but low abundances in smectite (~30%)
376 and kaolinite (~5-10%), in comparison to the subsequent *ca.* 31-17.2 ka interval. Similarly,
377 the smectite content abruptly decreases from *ca.* 17.2 ka ($<10\%$) while the content in kaolinite
378 (up to 25%) and illite (up to 60-70%) significantly increases. Note that despite a general low
379 abundance, kaolinite is the only clay mineral to show a distinct signature for the three time
380 periods considered.

381 The Danube River tributary samples ($n=12$) were divided into three groups corresponding to
382 the north-eastern Alps ($n=5$), the Carpathians ($n=5$) and the Dinarides ($n=2$) mountainous
383 areas (Table 3). River samples from the Alps show an illite content of ~40-50% while chlorite
384 represents ~25% of the clayey fractions. Kaolinite and smectite contents are low, usually
385 <5%, except in the Iller River where the smectite content reaches 40%. Smectite (~55%)
386 dominates over illite (~25-30%) in the Carpathians, while an inverse pattern is observed in the
387 Dinarides (~45-50% and ~20-25% of illite and smectite, respectively). The clay mineralogy of
388 these zones contrasts with that of the north-eastern Alps with significant abundance of
389 kaolinite (~10-20%) and very low content of dolomite (<2%). Dolomite abundance is
390 significant (up to 17%) in the Alpine rivers.

391

392 6.3.2 Illite crystallinity index

393 The illite crystallinity index (ICr) in GAS-CS01 ($n=146$) shows values ranging from ~0.25° at
394 the core bottom to ~0.60° in the Red Layers interval (Fig. 10f and Supplementary Online
395 Material). In between, the ICr values range from ~0.30° to 0.40°. The increase in ICr values
396 in the Red Layers is abrupt (at *ca.* 17.2 ka). In contrast, the ICr decreases gradually from *ca.*
397 33.5 ka to *ca.* 30 ka.

398 The ICr values of the Danube tributary river samples ($n=12$) are more homogeneous than in
399 core GAS-CS01. ICr values reach a maximum of only 0.34-0.39° in the northern Alps (Iller
400 River and the Danube at Passau). The ICr minimum (0.20°) is found in the (upper) Drava
401 River sample, eastern Alps (Table 3).

402

403 6.3.3 ϵ_{Nd}

404 The ϵ_{Nd} dataset used in this study is from core MD04-2790 ($n=84$) for the *ca.* 28-10 ka period
405 (Soulet et al., 2013) and from core GAS-CS01 ($n=14$) for the *ca.* 32-28 ka period (Fig. 10g).
406 GAS-CS01 sediment show an ϵ_{Nd} value of -11.0 at *ca.* 28 ka, in line with the ϵ_{Nd} signature of -
407 11.3 ± 0.3 ($n=53$) for the glacial MD04-2790 sediment (except Red Layers, see the discussion
408 below). ϵ_{Nd} values gradually change towards the core bottom, reaching about -9.4 ± 0.1 ($n=9$)
409 over the *ca.* 33.5-31 ka period (Supplementary Online Material).

410

411 7. DISCUSSION

412

413 7.1 Linking GAS-CS01 and MD04-2790 sedimentary sequences to Central European 414 rivers

415

416 **7.1.1 Sedimentological evidence for direct connection between Central European** 417 **sediment sources and Black Sea depositional sinks**

418 The sedimentological investigation of core GAS-CS01 shows that the continuous, rhythmic
419 layering observed throughout the core (Fig. 4) consists in the succession of coarsening-
420 upward and fining-upward units characteristics of hyperpycnal turbidity-current deposits (*i.e.*
421 hyperpycnites; Mulder et al., 2003), at both the decimetre (lower part of GAS-CS01; Fig. 7)
422 and millimetre scales (upper part of the core; Fig. 9). Thus, we attribute each clastic rhythmite
423 (laminae or beds; Fig. 4) in GAS-CS01 to a discrete hyperpycnal flow. Hyperpycnal flows are
424 defined as a bottom-riding flow evolving from a hyperpycnal plume, which descends to the
425 basin floor as a result of excess density generated by its sediment load. Hyperpycnal flows are
426 thus seen as the continuation of river discharges (*i.e.* floods) in subaqueous environments
427 (Mulder et al., 2003, 1998; Mulder and Syvitski, 1995; Normark and Piper, 1991; Piper and
428 Normark, 2009). They are frequent in freshwater lakes where only small particle density
429 thresholds are necessary to trigger plunging (Mulder et al., 2003). The brackish water
430 conditions prevailing in the Black Sea during the last glacial period (Deuser, 1972; Marret et
431 al., 2009; Ross et al., 1970; Schumilovskikh et al., 2014; Soulet et al., 2010; Wegwerth et al.,
432 2016), combined with the increased surface runoff and sediment load of the western Black
433 Sea rivers (*e.g.* Danube, Dniepr) due to the combination of reduced vegetation cover and
434 widespread permafrost (Kasse et al., 2010; Sidorchuk et al., 2011, 2008) likely favoured the
435 generation of hyperpycnal flows and their deposits at the GAS-CS01 site. The recording of
436 these events, and by extension of the river floods, was also favoured by the proximity to the
437 GAS-CS01 site and the delta of the western Black Sea rivers. Indeed, the glacial lowstand
438 conditions (lake level ~90-120 m below the present sea level; Figs 1 and 2) significantly
439 reduced the river mouth distance to the shelf margin. This evidence suggests that the 3815
440 hyperpycnites of core GAS-CS01 provides a high-resolution flood record in the north-west
441 Black Sea over the *ca.* 33.5-15 ka interval. Similarities in both the stratigraphy (see the XRF
442 Ca_{norm} for a prominent example; Fig 5) and sedimentology (*i.e.* rhythmic layering throughout;
443 Fig. 6) observed in core MD04-2790 (Soulet et al., 2011a), ~20 km east of GAS-CS01,
444 highlights the regional imprint of river floods in the north-western part of the glacial Black
445 Sea 'Lake'.

446 Reconstructed hyperpycnite frequency indicates that both GAS-CS01 and MD04-2790 sites
447 experienced five main periods of increased flood frequency (F_x), each of 1.5-3 kyr duration,
448 over the *ca.* 33.5-15 ka interval. These periods occurred simultaneously at both sites, at

449 *ca.* 32.5-30.5 ka (F₅), corresponding to the peak maximum, and at *ca.* 29-27.5 ka (F₄),
450 *ca.* 25.3-23.8 ka (F₃), *ca.* 22.3-19 ka (F₂) and *ca.* 17.2-15.7 ka (F₁) (Fig. 10b,c). The
451 simultaneity of each of the F_x periods at sites GAS-CS01 and MD04-2790 importantly
452 suggests a common forcing and, potentially, a unique river source at the two sites. This is
453 fittingly demonstrated for the F₁ period, *ca.* 17.2-15.7 ka. Geochemical investigations of
454 MD04-2790 sediment and the use of neodymium isotopic composition show that the sediment
455 composing the Red Layers originated from the decaying FIS and were transported to the
456 Black Sea by the Dniepr River (Soulet et al., 2013). Thus, the F₁ peak in GAS-CS01 and
457 MD04-2790 result from the increase in the frequency of hyperpycnal flows generated at the
458 Dniepr River mouth in response to ice mass fluctuations ~1,200 km northward (Fig. 1; Soulet
459 et al., 2013). The available geochemical dataset reveals that the unique, major river source for
460 hyperpycnal flows over the *ca.* 33.5-17.2 ka interval and the F₂, F₃, F₄ and F₅ peaks was the
461 Danube River (see Part 7.1.2). The concomitance between climate, sediment input and
462 geochemical signature changes (smectite abundance, ε_{Nd}, etc.; Fig. 10) excludes both an
463 autogenic origin (*i.e.* internally generated ‘noise’) and lake-level changes (highly debated over
464 the last glacial period; see Lericolais et al., 2011 and Vidal et al., 2010 for contrasting
465 conclusions) for the observed variability in the sedimentary record at the GAS-CS01 and
466 MD04-2790 sites (see Part 7.2).

467

468 **7.1.2 Deciphering river sources**

469 7.1.2.1 Neodymium isotopic composition

470 The sediment of the Red Layers deposited between *ca.* 17.2 and 15.7 ka (F₁ peak) are
471 characterised by ε_{Nd} values of -14.5 ± 1.3 (down to -18; $n=24$; Soulet et al., 2013). These
472 values are close to ε_{Nd} values of sediments of the Baltic area (Boswell et al., 2019, 2018;
473 Soulet et al., 2013; Toucanne et al., 2015) and the rivers Dniepr (ε_{Nd} of -14; Soulet et al.,
474 2013) and Don (-14.3, this study) showing that the Red Layer sediments originated from the
475 decaying FIS (Soulet et al., 2013). In contrast, the glacial sediment in MD04-2790, from
476 *ca.* 28 ka (oldest ε_{Nd} analysis in Soulet et al., 2013) to 11.7 ka shows homogenous but very
477 distinct ε_{Nd} values of -11.3 ± 0.3 ($n=53$). The latter signature is close to that of the European
478 Alps (Soulet et al., 2013), for which the northern and eastern parts (sediment yield of 160 and
479 220 t.km².yr⁻¹, respectively; Hinderer et al., 2013) represent a substantial contribution to the
480 Danube sediment discharge (mean sediment yield: 83 t.km².yr⁻¹). Indeed, Alpine rivers carry
481 fine-grained sediments with modern ε_{Nd} values ranging from about -10.8 for the Pô River

482 (south-western Alps; Frost et al., 1986), -10.2 ± 0.5 for the Rhône River (western Alps; Henry
483 et al., 1994) and -9 for the Rhine (north-western Alps; Bayon et al., 2015) and the Danube
484 (north-eastern Alps) rivers (Soulet et al., 2013). The Nd isotopic values of these Alpine rivers
485 match those of the Quaternary loess of the Carpathian Basin (-10.4 ± 0.6 , $n=20$; Újvári et al.,
486 2012). Based on the above, we thus assume that the glacial ϵ_{Nd} signatures of -11.3 ± 0.3 at site
487 MD04-2790 are mainly ascribed to the Alps-Carpathian realm and, by extension, to the
488 Danube River. Nevertheless, it cannot be ruled out that a slight contribution from the Dniepr
489 and Don (ϵ_{Nd} of about -14) at the studied sites possibly lowered the ‘pure’ ϵ_{Nd} signature ($-11/-$
490 9) of the Danube to its lower (*i.e.* unradiogenic) end members during the last glacial period.
491 This mixing is supported by the significant increase in ϵ_{Nd} at *ca.* 33-31 ka (F_5 peak), with
492 radiogenic values (about -9) that undoubtedly excludes all river sources except that of the
493 Danube at that time.

494

495 7.1.2.2 Clay mineralogy and illite crystallinity

496 Illite and smectite dominates the clay mineralogy of GAS-CS01 sediment (Fig. 10d). Illite is a
497 good marker for northern river sources in the Black Sea (Stoffers and Müller, 1978; Tudryn et
498 al., 2016), including the Danube River (Table 3), but it shows a maximal abundance ($>40\%$)
499 both during the ‘non-radiogenic’ Dniepr-sourced F_1 peak (*i.e.* Red Layers; ϵ_{Nd} down to -18)
500 and the ‘radiogenic’ Danube-sourced F_5 peak (ϵ_{Nd} about -9). Thus, it cannot be used to
501 decipher sediment sources in the north-west Black Sea. The combination of illite with
502 kaolinite at GAS-CS01 during the F_1 peak is a peculiar mineralogical signature over the
503 studied interval. Illite and kaolinite are typical of (paleo)soils, pedogenic processes and long-
504 term weathering of sedimentary basins (Chamley, 1989) and appear as the main clay minerals
505 in the Volga and Dniepr-Donets basins (Makshaev and Svitoch, 2016; Misch et al., 2018;
506 Vishnevskaya and Sedaeva, 2000), thus supporting an eastern Central European origin for the
507 deposition of Red Layers (Soulet et al., 2013). On the other hand, the low kaolinite content
508 ($\sim 5-15\%$), together with the ϵ_{Nd} values, exclude this source (at least as a major contributor)
509 for glacial sediment input to the margin between *ca.* 33.5 and 17.2 ka.

510 Smectite content is low to absent in the Red Layers but represents 30 to 60% of the *ca.* 33.5-
511 17.2 ka interval at GAS-CS01. Smectite is well-represented in the Danube drainage basin
512 (Tudryn et al., 2016), particularly in the Dinarides ($\sim 20-25\%$) and the Carpathians ($\sim 45-55\%$;
513 Table 3). In the latter region, it probably originates from chemical hydrothermal weathering of
514 volcanic rocks (Chamley, 1989), as shown in the Tisza basin (*e.g.* Tokaj Mountains and the

515 Calimani-Gurghiu-Hargita volcanic chain in the northern and eastern Carpathians,
516 respectively; Bobos, 2012; Kiss et al., 2010). In the Alpine domain of the Danube, smectite is
517 restricted to the western part of the Molasse Basin as shown by mineralogical data from the
518 Iller River (40%; [Table 3](#)) and the neighbouring Lake Constance (Müller and Quakernaat,
519 1969). It is important to note that the Rhine glacier covered Lake Constance during the last
520 glacial period and drained into the Danube (Ellwanger et al., 2011), thus providing a
521 significant source of Alpine smectite, with chlorite and dolomite (Müller and Quakernaat,
522 1969; Schmieder et al., 2004), to the north-west Black Sea. Chlorite content is also significant
523 (~25-30%) in the Alpine domain, in rivers draining both the northern (*e.g.* Inn, Enns) and
524 central eastern Alps (*i.e.* eastern Dolomites and the Drava River; [Table 3](#)), where physical
525 weathering at high altitudes dominates (Chamley, 1989; Müller and Quakernaat, 1969).
526 Chlorite content in GAS-CS01 reaches a maximum (~25%) during the F₅ peak together with
527 an increase in dolomite (~10%), a common mineral in the inner Alps (Upper Rhine, Iller,
528 Enns, Drava; [Table 3](#)). Thus, the mineralogical signature for the F₅ peak suggests a significant
529 Alpine contribution. More generally, these data together with ϵ_{Nd} support our contention that
530 the Danube River was the main source for sediment input to the margin over the *ca.* 33.5-
531 17.2 ka interval.

532 This is further supported by the ICr values of 0.32 ± 0.04 at GAS-CS01 ([Fig. 10f](#)) that fit well
533 with those obtained for the Danube river samples (0.3 ± 0.05 ; [Table 3](#)). Such values are
534 indicative of illite formation in low-grade metamorphic, high anchizonal conditions (*i.e.* lower
535 greenschist facies; Kubler, 1967), typical of the central and eastern Alps (Bousquet et al.,
536 2008; Krumm et al., 1988; Rantitsch, 1997; Schramm, 1991), the Dinarides (Rainer et al.,
537 2002) and the Carpathians (Árkai, 1991; Árkai et al., 2003; Ciulavu et al., 2008).
538 Interestingly, the F₅ peak shows ICr values down to 0.23° pointing to anchizonal-epizonal
539 thermal conditions (*i.e.* blueschist facies). Such metamorphic conditions are restricted to the
540 western (Gemser and Bükk units; Árkai, 1991) and southern parts (Danubian window; Ciulavu
541 et al., 2008) of the Carpathians, and the Engadine (up to 4,049 m at Piz Bernina) and Tauer
542 (up to 3,898 m at Grossglockner) windows of the eastern and central Alps, respectively
543 (Bousquet et al., 2008; Nievergelt et al., 1996; Schramm, 1991) ([Figs 1 and 3](#)). The dolomite
544 enrichment at *ca.* 33-31 ka together with the above ICr values, points to these high alpine
545 sources for the F₅ peak sediments, and by extension to the Drava (and its tributaries; *e.g.*
546 Mur), that drain both the Dolomites and the southern Tauer window, and the Inn rivers. The
547 Inn River has its source in the Bergell Massif (upper Engadine valley) and the Salzach River,
548 its main tributary, drained the northern part of the Tauer window ([Fig. 3](#)). Interestingly, the

549 ϵ_{Nd} values of the F₅ peak (-9.4 ± 0.1 , $n=9$) match with the lower range of ϵ_{Nd} values ($-$
550 8.0 ± 1.4 , $n=9$) determined for recent granites in the high Central Alps, including the Bergell
551 Massif (Juteau et al., 1986). Altogether, the neodymium isotopic composition, the clay
552 mineralogy and the ICr highlight the imprint of the Danube River on the north-west Black Sea
553 margin sedimentation during the *ca.* 33.5-17.2 ka interval.

554 The above finding is in line with geomorphological aspects from the continent interior to the
555 deep Black Sea. First, the modern contribution of the ‘mountainous’ Danube to the Black Sea
556 exceeds that of the ‘lowlands’ Dniester, Dnieper and Don by a factor 8 (see Part 2.1; Milliman
557 and Farnsworth, 2013; Milliman and Syvitski, 1992; Panin and Jipa, 2002), and this
558 difference was strongly enhanced during the last glacial period by the presence of the AIS and
559 Carpathian glaciers in the Danube drainage area (see Part 2.2). In contrast, the southern limb
560 of the FIS entered the Upper Dniepr basin only during a short period *ca.* 20-17 ka (Hughes et
561 al., 2016; Karabanov and Matveyev, 2011; Soulet et al., 2013) (Fig. 1). Moreover, the
562 physiography of the shelf-penetrating Danube Canyon (Popescu et al., 2004) and the high
563 sediment inputs into the Danube deep-sea fan (Constantinescu et al., 2015) are indicative of
564 both a high Danube sediment discharge and of a good connectivity between the Danube delta
565 and the shelf margin where cores GAS-CS01 and MD04-2790 are located (Fig. 2). As such,
566 the physiography of the margin suggests that the GAS-CS01 site was located at only ~20-
567 30 km (~50 km for MD04-2790) from the Danube paleo-delta front (~130 km today) during
568 glacial lowstand conditions (Popescu et al., 2004). Sediments deposited at sites GAS-CS01
569 and MD04-2790 between *ca.* 33.5 and 17.2 ka therefore record the evolution of the Danube
570 basin.

571

572 **7.2 From the Black Sea sedimentary record to the Alpine Ice Sheet**

573

574 The above geochemical constraints, together with the timing for the F₅ (*ca.* 32.5-30.5 ka), F₄
575 (*ca.* 29-27.5 ka), F₃ (*ca.* 25.3-23.8 ka) and F₂ (*ca.* 22.3 to 19 ka) peaks, suggest increased
576 Danube sediment discharges during Heinrich Stadial (HS; *i.e.* a stadial which contains a
577 Heinrich event as defined by Sanchez Goñi and Harrison, 2010) 3 (*ca.* 32-29 ka), Greenland
578 Stadial 4 (*ca.* 28.6-27.8 ka), HS 2 (*ca.* 26-23.5 ka) and during the period corresponding to the
579 transition from the global LGM to the Northern Hemisphere deglaciation, respectively. This
580 correlation highlights a close relationship between Danube River flood frequency and climate
581 change. Nowadays, severe floods in the Alpine-Carpathian range are triggered by heavy, late
582 spring to fall precipitation (*e.g.* Blöschl et al., 2013; Parajka et al., 2010). Holocene

583 reconstructions of the flood frequency in the central and north-eastern Alps reveal centennial-
584 to millennial-scale fluctuations in flood activity, with high flood activity correlated with cool
585 periods (lows in solar activity, global/alpine glacier advances; Glur et al., 2013; Swierczynski
586 et al., 2013; Wirth et al., 2013).

587 During the last glacial period, the continental ice build-up promoted cooling and enhanced
588 aridity over Europe (Wu et al., 2007). Precipitation over the Alps and Carpathians occurred
589 mainly in the form of snow. This inhibited the generation of floods from high-altitude sites,
590 but participated in the build-up of glaciers over the Carpathians and of the AIS during the last
591 glacial period (Figs 1 and 3). The AIS built up, reached its glacial maximum extent (covering
592 up to ~50,000 km² of the Danube watershed) and thickness (up to 2,500 m in the Hohe Tauern
593 region; Figs 3 and 11), and eventually shrunk over the *ca.* 33-17.2 ka interval (*e.g.* Ivy-Ochs,
594 2015; Ivy-Ochs et al., 2008; Seguinot et al., 2018). Pullback of glaciers from their maximum
595 extent (*i.e.* Alpine LGM) was underway by *ca.* 24-22 ka, and glaciers had receded within the
596 mountain front by *ca.* 19-18 ka (*e.g.* Ivy-Ochs, 2015; Monegato et al., 2017; Reitner, 2007).
597 This has been widely documented in the north-eastern Alps, including the Rhine, Iller, Isar,
598 Loisach, Inn, Salzach, Enns and Drava valleys (Ellwanger et al., 2011; Habbe and Rögner,
599 1989; Heiri et al., 2014; Ivy-Ochs et al., 2008; Preusser, 2004; Reitner, 2012; Spötl et al.,
600 2013; Starnberger et al., 2009; Van Husen, 2004). Thus, glaciers retreat must have supplied
601 meltwater and sediment to the to the Danube sediment routing system.

602 The timing for the Alpine (and Carpathian; Makos et al., 2018, 2013) deglaciation closely
603 matches that of enhanced Danube river floods from *ca.* 22 to 19 ka (F₂ peak). This strongly
604 suggests that the F₂ peak originated from the rapid downstream transport of glacial
605 sediments by AIS (and possibly Carpathian glaciers) meltwater, an assumption supported by
606 the glacial character of the lithic grains found in GAS-CS01 (Supplementary Fig. S3).
607 Onshore ice retreat and concomitant offshore sediment pulse is a common feature of large-
608 scale glaciated sediment routing systems (*e.g.* Mississippi in North America, Kolla and
609 Perlmutter, 1993; Channel River, Rhine, Rhone or Po in Europe, Bonneau et al., 2017;
610 Hinderer, 2001; Pellegrini et al., 2017; Toucanne et al., 2010). In these systems, sediment
611 production greatly exceeds transport capacity, hence downstream release of sediments occurs
612 through pulses of meltwater floods when glaciers retreat. Thus, the F₂ peak (sourced by the
613 AIS-Danube system) as well as the F₁ peak (sourced by the FIS-Dniepr system; Soulet et al.,
614 2013) share the common genetic origin of ice melting. Together with the geochemical results,
615 we thus suggest that the F₅ (*ca.* 32.5-30.5 ka), F₄ (*ca.* 29-27.5 ka) and F₃ (*ca.* 25.3-23.8 ka)

616 peaks, just like F₂, were triggered by significant ice melting and meltwater production in the
617 Danube basin.

618 Little is known about ice fluctuation in the Alps before the deglaciation (*e.g.* Ivy-Ochs et al.,
619 2008). The Tagliamento end moraine system of the south-eastern Alps (Fig. 3) provides
620 insights into AIS fluctuations at the LGM. Two phases of glacial culmination occurred from
621 26.5 ka and at *ca.* 23-21 ka, separated by a distinct recession which ended no later than
622 *ca.* 23 ka (Monegato et al., 2017) (Fig. 12e). This recession, also recognized in the
623 neighbouring Brenta glacier region (Rossato and Mozzi, 2016; Fig. 3), is concomitant with
624 enhanced Danube river floods and the F₃ peak, while the two glacier advances are coeval with
625 the minima in the Danube River discharge at *ca.* 27-25.3 ka and from *ca.* 23.8 ka (Fig. 12b).
626 The Tagliamento and Brenta glaciers were draining south into the Adriatic, suggesting that
627 the timing of ice fluctuations in the Danube basin was similar to that of the south-eastern Alps
628 with a significant melting episode at *ca.* 25.3-23.8 ka (F₃ peak). The hypothesis is supported
629 by the fact that both the Tagliamento and Brenta glaciers in the south-eastern Alps, and the
630 Inn, Salzach, Traun, Mur and Drava glaciers in the Danube basin were all draining the Hohe
631 Tauern region and the Engadine ice dome in the central eastern Alps (Florineth and
632 Schlüchter, 2000; Seguinot et al., 2018; Fig. 3). Geochemical data characterizing the GAS-
633 CS01 sediment during F₅ peak (high ϵ_{Nd} and dolomite content, and low ICr; see Part 7.1 and
634 Fig. 10) also suggest this region as the source of sediment.

635 F₅ peak in hyperpycnal flow frequency suggests a significant retreat of the AIS at *ca.* 32.5-
636 30.5 ka, with significant remobilization (via meltwater) of the glacial sediment from the
637 Engadine (*e.g.* upper Inn) and Tauern (*e.g.* upper Salzach and Drava) valleys. By extension,
638 this indicates that ice caps were mainly restricted to the high Central Alps before *ca.* 32 ka,
639 with a configuration that could resemble that proposed in Figure 11. This is consistent with
640 the radiocarbon chronology of the Inn Valley that indicates that glaciers were upstream of
641 (but close to) the Innsbruck region (*i.e.* ~100 km of the Alpine foreland) *ca.* 33-32 ka (Spötl et
642 al., 2013). It is noteworthy that the sediment flux at the GAS-CS01 and MD04-2790 sites was
643 greater during the F₅ peak than during the F₂, F₃, and F₄ peaks. The amplitude of the F₅ peak
644 could be explained by very low lake-level conditions, basinward migration of the Danube
645 delta or even lateral changes in sediment dispersal and depocenter considering the fact that the
646 F₅ peak is higher at site GAS-CS01 than at site MD04-2790 (Fig. 10). However, these
647 forcings alone cannot explain the alpine geochemical signature (*i.e.* high Central Alps)
648 observed at that time. As a result, we propose that the F₅ peak (as well as the F₄ peak, see
649 below) is the result of a short term glacier retreat event that occurred in the course of the

650 longer term growing phase of the AIS toward its LGM extent. Resulting pulse in meltwater
651 flood flushed a huge amount of glacial material (*i.e.* no longer available) accumulated in
652 the high Alps since the previous glaciation (MIS 4 or even before; Ivy-Ochs et al., 2008; van
653 Husen, 2000). In addition, our results suggest that the rapid ice growth that led to the invasion
654 of the northern Alpine foreland by the major AIS ice-streams at the LGM started after
655 *ca.* 30.5 ka, *i.e.* after the retreat interval mirrored by the F₅ peak, and ended no later than
656 *ca.* 25.3 ka (onset of the F₃ peak). Such timing is consistent with that reported for the western
657 Carpathians (Makos et al., 2018) and the northern foreland of the Swiss Alps (*e.g.* Rhine
658 glacier; Preusser et al., 2011) (Fig. 12d). Finally, the F₄ peak suggests that the LGM ice
659 advance was interrupted (with glaciers melting in the north-eastern Alps) between *ca.* 29 and
660 27.5 ka. Our results imply that the ice front in the Inn Valley (Spötl et al., 2013) advanced to
661 its LGM position at a rate of about 20-45 m/year (~100 km in a maximum of 2,200-5,200
662 years).

663 This rapid change in AIS volume and extent modified the regional pattern of erosion (*e.g.* Jiao
664 et al., 2018), which may explain the mineralogical changes observed at the GAS-CS01 site
665 after the F₅ peak. This includes in particular the dominance of smectite in clay assemblages
666 (Fig. 10d) and the disappearance of the signature (ICr, ϵ_{Nd} ; Fig. 10f,g) of the Engadine and
667 Tauern source areas. These two regions were rapidly covered by ice (>1 km in thickness at the
668 LGM; Florineth and Schlüchter, 2000) and the sediment-laden meltwater reaching the north-
669 west Black Sea then mainly originated from the ice-streams located in the northern Alpine
670 foreland, including those of the Rhine (Ellwanger et al., 2011) and the Iller valleys (Habbe
671 and Rögner, 1989) that remobilize smectite-rich sediments (Müller and Quakernaat, 1969;
672 Table 3) (Fig. 11).

673 It is striking how Danube River flood activity *ca.* 33-17 ka closely resembles that of the Po
674 River, Italy (Fig. 12c). Indeed, the F₅, F₄, F₃ and F₂ Danube peaks are coeval with rapid
675 increases in sediment flux (up to 200 km³/kyr) in the Po delta, which accumulated ~350 m of
676 sediment from the southern AIS *ca.* 32-14 ka (Pellegrini et al., 2018, 2017). This result
677 indicates that the sediment flux of the Danube and Po rivers was not controlled by basin base
678 level changes (*i.e.* water-level fluctuations) because they evolved independently in the
679 Mediterranean and Black Seas during glacial periods (Badertscher et al., 2011). Hence, AIS
680 mass-balance changes must explain the similar sediment flux pattern observed offshore of the
681 Po and Danube rivers during glacial times. The close resemblance between AIS fluctuations
682 in the Danube catchment and the regional precipitation pattern (*i.e.* 7H $\delta^{18}O$ record of the

683 Sieben cave system; Luetscher et al., 2015), that partly controlled glacier mass balance
684 (Fig. 12d), suggests that the AIS as a whole was responding to large-scale climate forcing.

685

686 **7.3 Enhanced surface melting of the Alpine Ice Sheet during periods of North Atlantic** 687 **cooling**

688

689 In the above discussion, we have showed that the F₅ (ca. 32.5-30.5 ka), F₄ (ca. 29-27.5 ka), F₃
690 (ca. 25.3-23.8 ka) and F₂ (ca. 22.3 to 19 ka) peaks in hyperpycnal flow frequency, resulting
691 from increased Danube sediment discharges, likely resulted from enhanced surface melting of
692 the AIS during HS 3 (ca. 32-29 ka), Greenland Stadial 4 (ca. 28.6-27.8 ka), HS 2 (ca. 26-
693 23.5 ka) and the very end of the global LGM. The timing of these episodes of AIS melting has
694 important implications, at regional to continental scales. The last episode of AIS melting
695 recorded in this study (*i.e.* F₂ peak in the Danube record, and its equivalent in the Po delta)
696 occurred ca. 22-19 ka. This time interval corresponds to the onset of the widespread retreat of
697 the Northern Hemisphere ice sheets in response to high northern latitude summer insolation
698 forcing (Carlson and Clark, 2012; Clark et al., 2009). This event is well-documented for the
699 FIS that rapidly retreated in the Baltic lowlands at that time (Hughes et al., 2016; Larsen et al.,
700 2009; Stroeve et al., 2016; Toucanne et al., 2015, 2010). In contrast, the rapid acceleration in
701 the FIS retreat from ca. 18 ka (HS 1; Hughes et al., 2016; Toucanne et al., 2015, 2010;
702 Zaragosi et al., 2001) has no AIS equivalent in the north-west Danube and Po sedimentary
703 records. Sediment flushed by AIS fluctuations younger than ca. 19 ka (*i.e.* Alpine Lateglacial,
704 including the Gschnitz stadial ca. 17-16 ka; Ivy-Ochs, 2015) could have been trapped in
705 glacier-shaped lake basins that formed during deglaciation (Hinderer, 2001). This is consistent
706 with the idea that glaciers receded back into the mountain front during the ca. 22-19 ka
707 melting event, especially in the north-eastern Alps (Ivy-Ochs, 2015; Reitner, 2007; van
708 Husen, 2000). By extension, this suggests that the HS 1 melting episode (ca. 18-16.5 ka;
709 Toucanne et al., 2015), if it existed at all in the Alps (*e.g.* Ravazzi et al., 2014; Wirsig et al.,
710 2016; Lehmann et al., 2020), impacted only a restricted area and volume of ice. This implies
711 that the forcing that caused the initial retreat of the FIS at ca. 22-19 ka was important enough
712 to cause a catastrophic collapse of the AIS. The rapid AIS collapse from ca. 22 ka was likely
713 forced by the summer energy of Huybers (2006) that increase from 23.5 ka at 45°N and
714 precede the summer insolation by 1.5 kyr (22 ka at 45°N; Laskar et al., 2004) (Fig. 12e). This
715 suggests that summer energy is a better indicator of glacial variability than insolation intensity

716 (Huybers, 2006), and confirms that the AIS was a highly dynamic ice-sheet (Seguinot et al.,
717 2018).

718 AIS melting events during HS 3 and HS 2 in both the Danube and Po catchments (Fig. 12c)
719 and the substantial FIS recession in the Baltic lowlands (Boswell et al., 2019; Hughes et al.,
720 2016; Toucanne et al., 2015) are concomitant within age-model uncertainties. HS 3 and HS 2
721 in the North Atlantic correspond to cold air and sea-surface temperatures, widespread sea ice
722 and increased iceberg calving and dispersal from surrounding marine-terminating ice margins
723 (Bard et al., 2000; Barker et al., 2009). This is in contrast to the expectation that ice sheets
724 should expand in colder climates and shrink in warmer climates, given constant precipitation.
725 Considering that ablation of land-based ice in mid-latitudes occurs primarily during summer
726 months (Oerlemans et al., 2001), the melting of both the AIS and the FIS during HS 3 and
727 HS 2 (as well as during Greenland Stadial 4 for the AIS) requires a high seasonality in
728 western Europe. High seasonality implies enhanced summertime melting, and thus rising
729 summer temperature, despite severely cool winters and the rapid expansion of sea ice in the
730 North Atlantic as previously discussed by Buizert et al. (2014) and Denton et al. (2005, 2010)
731 for HS 1 and the Younger Dryas cold reversal. High-resolution climate simulations and proxy
732 evidence, including the disintegration of Alps glaciers and the Scottish ice cap, support the
733 occurrence of warm European summers during HS 1 (*i.e.* the so-called Gschnitz stadial in the
734 Alps; Lehmann et al., 2020) and the Younger Dryas (Bromley et al., 2018; Schenk et al.,
735 2018; Magyari et al., 2019). The atmospheric blocking of cold westerly winds over western
736 Europe would be a key mechanism according to Schenk et al. (2018) and such a forcing
737 would have prevailed during HSs of the last glacial period. A strong shift in atmospheric
738 circulation in Europe and over the Alps during and around the LGM (Becker et al., 2016;
739 Beghin et al., 2015; Florineth and Schlüchter, 2000; Ludwig et al., 2016), including
740 millennial-scale climate changes (Luetscher et al., 2015; Monegato et al., 2017), partly
741 support this assumption. Whatever the mechanism responsible for driving stadial decay of the
742 AIS, our results, together with those obtained for the FIS for the last (Toucanne et al., 2015)
743 and penultimate glacial periods (Boswell et al., 2019), strengthens the idea that warm
744 European summers are likely a recurring feature of North Atlantic stadials.

745

746 **8. CONCLUSION**

747

748 The GAS-CS01 and MD04-2790 glacial sedimentary sequences of the Black Sea 'Lake'
749 provide a continuous high-resolution record of the Danube River discharge over the *ca.* 33-

750 17 ka period. The main results, based on sedimentological, mineralogical and geochemical
751 analysis, are the following:

752

753 1. The Danube sediment routing system produced hyperpycnal discharges into the north-west
754 Black Sea throughout the study interval, and their deposits (*i.e.* hyperpycnites) at the GAS-
755 CS01 and MD04-2790 sites provide a continuous, high-resolution paleoflood record of the
756 Danube River at the end of the last glacial period (*ca.* 33-17 ka);

757

758 2. Four main periods of enhanced Danube flood frequency (F_x), each of 1.5-3 kyr duration,
759 are recorded at *ca.* 32.5-30.5 ka (F_5), at *ca.* 29-27.5 ka (F_4), at *ca.* 25.3-23.8 ka (F_3) and at
760 *ca.* 22.3-19 ka (F_2). The sediment of the F_2 period are typical of the Alpine foreland, whereas
761 that deposited during the F_5 period shows mineralogical and geochemical signatures typical of
762 the inner Alps (*i.e.* Engadine and Taurin windows). This suggests that the Danube River
763 activity over the *ca.* 33-17 ka interval provides a valuable record of paleoenvironmental
764 changes in the European Alps, and by extension of the north-eastern AIS, from the second
765 part of MIS 3 to the deglaciation;

766

767 3. Our data and continental morphostratigraphical evidence, suggest that the AIS volume has
768 drastically decreased at *ca.* 19 ka (and as soon as *ca.* 22 ka) since no fluctuation of the AIS is
769 recorded at the studied sites after this date. On the other hand, millennial-scale fluctuations of
770 the north-eastern AIS are recorded before the deglacial 22-19 ka event (F_2), with three
771 significant melting episodes, able to remobilize glacial sediment to the Black Sea, at
772 *ca.* 32.5-30.5 ka (F_5), at *ca.* 29-27.5 ka (F_4) and at *ca.* 25.3-23.8 ka (F_3). Ice advance occurred
773 between these periods and both the mineralogical and geochemical data suggest that the rapid
774 AIS growth from the inner Alps to its LGM position started from *ca.* 30.5 ka and ended no
775 later than *ca.* 25.3 ka;

776

777 4. The F_5 (*ca.* 32.5-30.5 ka), F_4 (*ca.* 29-27.5 ka) and F_3 (*ca.* 25.3-23.8 ka) events indicates
778 enhanced surface melting of the AIS during HS 3 (*ca.* 32-29 ka), Greenland Stadial 4
779 (*ca.* 28.6-27.8 ka) and HS 2 (*ca.* 26-23.5 ka) when severely cold winters and the rapid
780 expansion of sea ice prevailed in the North Atlantic. This new finding is in line with those
781 recently reported for the southern FIS and reinforces the emerging view that warm summers
782 and hence strong seasonality are key climatic features of western Europe during North
783 Atlantic stadials.

784

785 **ACKNOWLEDGMENTS**

786

787 The authors are very grateful to S. Ker, co-chief of the GHASS cruise; T. Dalle-Mulle, J.
788 Gouriou, A. Roubi, M. Rovere and M. Simon for technical support; B. Martin and S. Zaragosi
789 for the preparation of sediment thin sections; A. Trinquier for assistance on the Neptune MC-
790 ICPMS; E. Pelleter for the acquisition of the X-ray EDS maps; N. Gayet for the acquisition of
791 the SEM images; A. Banak, B. Dennielou, T. Gardes, G. Lericolais, A. Mena, R. Silva-
792 Jacinto, A. Van Exem and C. Zavala for invaluable discussions at various stages of this work;
793 A. Chalm for English improvements; and G. Monegato and two anonymous reviewers for
794 their helpful comments, which greatly improved the manuscript. Samples from river banks
795 were collected in one expedition by L.G. and two successive fieldwork seasons by a team
796 from ETH Zurich (the later reported in Freymond et al., 2017). Authors also thank the crew
797 and scientific teams of the ASSEMBLAGE (R/V Marion Dufresne) and GHASS (R/V
798 Pourquoi Pas?) cruises for the recovery of the long-piston cores MD04-2790 and GAS-CS01,
799 respectively. This work is a contribution to the ASSEMBLAGE project funded by the
800 European Commission (EVK3-CT-2002-00090) and to the BLAME project sponsored by the
801 French National Research Agency (ANR-18-CE01-0007). L.G. was supported by internal
802 grants from Woods Hole Oceanographic Institution. Data presented in this study are available
803 in the supplementary material, and through the SEANOE open-source online data repository
804 (<https://doi.org/10.17882/70660>).

805

806 **DATA AVAILABILITY**

807

808 Datasets related to this article can be found at <https://doi.org/10.17882/70660>, via the
809 SEANOE open-source online data repository.

810 **FIGURE CAPTIONS**

811

812 **Fig. 1:** Paleogeography of the Danube sediment routing system at the Last Glacial Maximum
813 (LGM) including the Alpine Ice-Sheet (AIS, ~130,000 km²; Ehlers and Gibbard, 2004), the
814 river course (~2,900 km; ~801,000 km²) from the Black Forest (Bf) to the (modern) Danube
815 delta (Dd), and the Danube deep-sea fan (Df; ~20,000 km²; Danube Canyon and channel-
816 levees in orange) in the Black Sea 'Lake' (level ~90-120 m below the present sea level;
817 paleoshoreline at -120 m in the Black and Adriatic Seas in light blue). A significant part of the
818 Rhine glacier (~14,000 km²; red arrows) drained into the Danube River at the LGM
819 (Ellwanger et al., 2011), thus increasing the AIS surface in the Danube watershed to ~50,000
820 km². Filled circles indicate the location of the modern river samples, with the colors referring
821 to the Alpine (white), Dinaric (purple) and Carpathians (green) sources. Orange circles refer
822 to the samples collected along the Danube mainstream (Table 3). Tagl.: Tagliamento glacier;
823 EW: Engadine window; TW: Tauern window (Alps); GW: Gemer-Bürkk window; DW:
824 Danubian window (Carpathians). White stars in the Black Sea indicate the location of cores
825 GAS-CS01 and MD04-2790. Black stars in the north-western Alps and the Adriatic Sea refer
826 to the Sieben Hengste cave system (7H; Luetscher et al., 2015) and the PRAD1-2 borehole
827 (Pellegrini et al., 2017, 2018) respectively. The limits of the Fennoscandian Ice Sheet (FIS) at
828 22 ka (continuous white line) and 17 ka (dashed white line) are also shown (Hughes et al.,
829 2016). The retreat of the FIS in the upper Dniepr from *ca.* 17 ka caused the deposition of the
830 Red Layers into the Black Sea (Soulet et al., 2013). Note the absence of an ice-sheet on the
831 Carpathians at the LGM.

832

833 **Fig. 2:** Detailed map of the north-western Black Sea margin showing the location of the long-
834 piston cores GAS-CS01 and MD04-2790 in front of the modern Danube delta. The numerous
835 canyons (including the shelf-penetrating Danube Canyon; Popescu et al., 2004) visible on the
836 continental slope are indicative of high Danube sediment discharge and of a good connectivity
837 between the Danube delta and the shelf margin during the last glacial period, when the Black
838 Sea was a giant freshwater lake and lowstand conditions dominated (see Part 2 for details).
839 Danube paleovalleys from Popescu et al. (2004).

840

841 **Fig. 3:** Detailed map of the eastern Alps showing (i) the main geographical and geological
842 features discussed in the main text, including the Tauern (TW) and Engadine (EW) windows
843 (Bousquet et al., 2008); (ii) the main rivers (blue lines) draining into the Danube River (except

844 the Rhine and Adige); (iii) the Alpine Ice-Sheet (AIS) at the LGM (Ehlers and Gibbard,
845 2004). The thick white line shows the AIS ice-divide at the LGM (based on Seguinot et al.,
846 2018). Star labeled 7H: Sieben Hengste cave system (Luetscher et al., 2015).

847

848 **Fig. 4:** Digital photographs and X-ray images of representative sections of the glacial
849 sequence of core GAS-CS01 (*i.e.* ‘banded lutites’ -Unit III- of Ross and Degens, 1974). Note
850 that the sequence is fully laminated, with clastic rhythmites evolving gradually downward from
851 millimetre- (*i.e.* laminae; Scandinavian-type lacustrine varves of Degens et al., 1978) to
852 decimetre-thick deposits (*i.e.* beds; megavarves of Degens et al., 1978). Clastic rhythmites in
853 GAS-CS01 are interpreted as hyperpycnite sequences. See [Figs 7, 8 and 9](#) for details.

854

855 **Fig. 5:** Stratigraphic correlation between cores GAS-CS01 (magenta line) and MD04-2790
856 (black line; Soulet et al., 2011a) based on XRF-Can_{orm} profiles. See section 5 ‘Age-depth
857 model’ and Supplementary Online Material for details, and [Table 2](#) for the radiocarbon dates.

858

859 **Fig. 6:** Depth-depth relationship between cores GAS-CS01 and MD04-2790 based on the
860 stratigraphic correlations shown in [Figure 5](#). See section 5 ‘Age-depth model’ and
861 Supplementary Online Material for details, and [Table 2](#) for the radiocarbon dates. The
862 laminae / bed thickness and the Red Layers interval are also shown. Note that sediment
863 accumulation rates (SAR) at site GAS-CS01 are significantly higher than at site MD04-2790
864 before *ca.* 31 ka (*i.e.* below depth 1595 cmbsf in core GAS-CS01 and depth 1990 cmbsf in
865 MD04-2790), consistent with the significant thickness difference of hyperpycnal beds
866 observed at the two sites on the same time interval. The decimeter-scale hyperpycnite beds
867 recognized in the lower part of core GAS-CS01 are detailed in [Figure 7](#).

868

869 **Fig. 7:** High-resolution analysis of the pluricentimeter-thick clastic rhythmites, interpreted as
870 hyperpycnites (H), observed in the basal part of core GAS-CS01 (>28.5 mbsf; here Section
871 34/34, 3139-3214 cmbsf; *ca.* 33 ka). **a**, Digital photograph; **b**, X-ray image and grey-level
872 measurements (yellow line); **c**, Hyperspectral image highlighting changes in the sediment
873 texture and/or composition. Colored circles refer to the grain-size analyses shown in **e** and **g**
874 (sedimentary sequences S1, S2 and S3); **d**, Schematic lithological succession based on grain-
875 size (**e**) and XRF (**f**) measurements. *Ha* and *Hb* correspond to the (basal) coarsening-up (*i.e.*
876 waxing period of river discharge) and (top) fining-up (*i.e.* waning period of discharge)
877 sequences of the hyperpycnites (Mulder et al., 2003) respectively. C: clay. S: silt-sand. **e**,

878 Grain-size measurements (median or D50, *i.e.* grain-size - μm - at which 50% of sample is
879 finer). Mean sampling resolution of 0.25 cm ($n=218$). Black arrows highlight some
880 representative coarsening-up and fining-up sequences. Colored circles refer to the grain-size
881 analyses shown in **c** and **g**; **f**, XRF Zr/Rb ratio, here used as a semi-quantitative grain-size
882 indicator (Dypvik and Harris, 2001); **g**, Particle size distribution of discrete sediment samples
883 (colored circles in **c** and **e**) from the coarsening-up sequences S1, S2 and S3.

884

885 **Fig. 8:** High-resolution analysis of the centimeter-thick clastic rhythmites, interpreted as
886 hyperpycnites (H), observed in the lower part of core GAS-CS01 (from ~22 to 28.5 mbsf;
887 here Section 30/34, 2804-2859 cmbsf; *ca.* 32 ka). **a**, Digital photograph; **b**, X-ray image and
888 grey-level measurements (yellow line); **c**, Hyperspectral image highlighting changes in the
889 sediment texture and/or composition. Colored circles refer to the grain-size analyses shown in
890 **e** and **g** (sedimentary sequences S1, S2, S3 and S4); **d**, Schematic lithological succession
891 based on grain-size (**e**) and XRF (**f**) measurements. *Ha* and *Hb* correspond to the (basal)
892 coarsening-up (*i.e.* waxing period of river discharge) and (top) fining-up (*i.e.* waning period
893 of discharge) sequences of the hyperpycnites (Mulder et al., 2003), respectively. C: clay. S:
894 silt-sand; **e**, Grain-size measurements (median or D50, *i.e.* grain-size - μm - at which 50% of
895 sample is finer). Mean sampling resolution of 0.25 cm ($n=149$). Black arrows highlight some
896 representative coarsening-up and fining-up sequences. Colored circles refer to the grain-size
897 analyses shown in **c** and **g**; **f**, XRF Zr/Rb ratio, here used as a semi-quantitative grain-size
898 indicator (Dypvik and Harris, 2001); **g**, Particle size distribution of discrete sediment samples
899 (colored circles in **c** and **e**) from the coarsening-up sequences S1, S2 and S3.

900

901 **Fig. 9:** High-resolution analysis of the subcentimeter-thick clastic rhythmites, interpreted as
902 hyperpycnites (H), observed in core GAS-CS01 (down to ~22 mbsf; here Section 22/34,
903 2031-2083 cmbsf; *ca.* 31 ka). **a**, Digital photograph; **b**, X-ray image and grey-level
904 measurements (yellow line); **c**, Hyperspectral image highlighting changes in the sediment
905 texture and/or composition; **d**, XRF Zr/Rb ratio, here used as a semi-quantitative grain-size
906 indicator (Dypvik and Harris, 2001); **e**, Focus on the XRF Zr/Rb ratio. The Zr/Rb variability,
907 similar to that observed for thicker clastic rhythmites in GAS-CS01 (Figs 7 and 8), suggest
908 coarsening-up and fining-up sequences; **f**, Thin section photograph (2039-2047.5 cmbsf)
909 showing subcentimeter-thick clastic rhythmites. White circles refer to the grain-size analyses
910 shown in **g**. Mean sampling resolution of 0.25 cm ($n=31$); **g**, SEM-EDX image of a
911 coarsening-up sequences (see the red square in **f** for location). The color variability highlights

912 the sediment geochemistry (see the color boxes). Coarse grains are mainly quartz (Si) and
913 dolomite grains (Mg, Ca). Note their angular character. Particle size distribution (white boxes)
914 for clayey ($n=9$) and silty ($n=5$) intervals are shown. A schematic lithological succession is
915 proposed on the right. *Ha* and *Hb* according to Mulder et al. (2003).

916

917 **Fig. 10: a**, $\delta^{18}\text{O}$ from GISP2 on the GICC05 timescale and the INTIMATE event stratigraphy.
918 Greenland Stadials (GS) and Greenland Interstadials (GI) are the Greenland expressions of
919 the characteristic Dansgaard-Oeschger events that represent cold and warm phases of the
920 North Atlantic region, respectively (Rasmussen et al., 2014). The Greenland synthetic $\delta^{18}\text{O}$
921 record (GLT_syn) of Barker et al. (2011), placed on the absolutely dated Chinese speleothem
922 record (Hulu Cave on this time interval), is also shown; **b, c**, Flood frequency and sediment
923 accumulation rates (SAR) off the Danube River, respectively; **d, e, f**, Clay mineralogy,
924 dolomite abundance and illite crystallinity (three-points average) at core GAS-CS01,
925 respectively. The green arrow highlights the increase in smectite content to higher values,
926 interpreted as the signature of the western Molasse Basin and Rhine glacier in response to the
927 rapid growth of the AIS (see Fig. 11 for details); **g**, Neodymium isotopic composition
928 (expressed in ϵNd) in core MD04-2790 (*ca.* 28-10 ka; Soulet et al., 2013) and GAS-CS01
929 (*ca.* 33.5-28 ka; this study) as a proxy for sediment provenance. The vertical light blue bars
930 highlight the timing for the F_5 (*ca.* 32.5-30.5 ka), F_4 (*ca.* 29-27.5 ka), F_3 (*ca.* 25.3-23.8 ka), F_2
931 (*ca.* 22.3- 19 ka) and F_1 (*ca.* 17.2-15.7 ka) peaks -based on both the flood frequency (**b**) and
932 the SAR (**c**)- interpreted as periods of enhanced flux of sediment-laden meltwater on the
933 north-west Black Sea margin. HS refers to Heinrich Stadials.

934

935 **Fig. 11:** Paleogeography of the central and eastern Alps, including the hydrographic network
936 (blue lines) and glacial limits (white shaded areas) at (a) *ca.* 33 ka (*i.e.* before Heinrich Stadial
937 3 = F_5 peak at the GAS-CS01 and MD04-2790 sites) and (b) during the local Last Glacial
938 Maximum (LGM; Ehlers and Gibbard, 2004), *ca.* 26 ka (*i.e.* before Heinrich Stadial 2 = F_3
939 peak). The proposed configuration at *ca.* 33 ka is based first on the geochemical evidences
940 (ICr , ϵNd) found at GAS-CS01 for significant inputs of terrigenous material from the Engadine
941 (EW) and Taurin (TW) windows (purple dashed lines; via the Inn, Salzach, Enns, Mur and
942 Drava rivers) into the north-west Black Sea *ca.* 32.5-30.5 ka (*i.e.* during the F_5 peak
943 interpreted as AIS melting; see the main text for details); and second, on the low content of
944 smectite at the GAS-CS01 site before *ca.* 30.5 ka (and until *ca.* 33.5 ka at least; Fig. 10d). The

945 smectite in the Alpine domain being restricted to the western part of the Molasse Basin (*e.g.*
946 Iller River; [Table 3](#)) and the upper Rhine (Müller and Quakernaat, 1969), the clay mineralogy
947 at GAS-CS01 suggests that these areas were mainly free of ice at *ca.* 33 ka (and until
948 *ca.* 30.5 ka) as shown in (a). Such an ice configuration (with the Iller, Lech and Isar/Loisach
949 rivers not connected to the AIS) is found using an equilibrium line altitude at ~2300 m above
950 sea level (white, high-altitude areas; also shown in (b) for comparison). Note that the invasion
951 of the northern Alpine foreland by the major AIS ice-streams (Alpine LGM) strongly
952 modified the glacial hydrographic pattern of the Alpine Danube. Smectite content at GAS-
953 CS01 suggests that the AIS growth (including the Iller glacier; Habbe and Rögner, 1989) and
954 the subsequent re-routing of the Rhine glacier meltwaters to the Danube (Ellwanger et al.,
955 2011) occurred from *ca.* 30.5 ka. The white arrows show the main sources for AIS meltwater
956 to the Danube. HS refers to Heinrich Stadials.

957

958 **Fig. 12:** **a**, $\delta^{18}\text{O}$ from GISP2 (Rasmussen et al., 2014) and the GLT_syn record (Barker et al.,
959 2011). See [Fig. 10a](#) for details; **b**, Flood frequency of the Danube River ([Fig. 10b](#)). The
960 dashed lines (between *ca.* 17.2 and 15.7 ka) correspond to the Dniepr River flood (Red
961 Layers; Soulet et al., 2013); **c**, Sediment volume of the Po River lowstand wedge, based on
962 seismic reflection data and the PRAD1-2 borehole ([Fig. 1](#); Pellegrini et al., 2017, 2018); **d**,
963 Ice-mass balance of the north-east AIS based on the Danube sediment records (open circles
964 and black line) and the 7H $\delta^{18}\text{O}$ record from the Sieben Hengste cave system, Switzerland
965 ([Figs 1 and 3](#); Luetscher et al., 2015). Thick blue arrows highlight AIS melting intervals,
966 meltwater production and sediment-laden meltwater inputs to the north-west Black Sea
967 margin (**b**); **d**, Fluctuations of the Rhine (purple; Preusser et al., 2011) and Tagliamento
968 (green; Monegato et al., 2007) glaciers. Arrows highlight the glaciers fluctuations discussed in
969 the main text; **e**, Summer energy (red line, $\tau \sim 400$) (Huybers, 2006) and 21 June-20 July
970 insolation for 45°N (blue line; Laskar et al., 2004). The vertical light blue bars highlight the
971 timing for the F₅ (*ca.* 32.5-30.5 ka), F₄ (*ca.* 29-27.5 ka), F₃ (*ca.* 25.3-23.8 ka), F₂ (*ca.* 22.3-
972 19 ka) and F₁ (*ca.* 17.2-15.7 ka) flood events. HS refers to Heinrich Stadials.

973 **TABLE CAPTIONS**

974

975 **Table 1:** Core locations.

976

977 **Table 2:** New radiocarbon (^{14}C) dates for cores GAS-CS01 and MD04-2790. Analyses were
978 carried out at the Beta Analytic radiocarbon dating laboratory (USA).

979

980 **Table 3:** Clay mineralogy of the Danube River and its main tributaries. Geographic
981 ‘mountainous’ clusters (raw -†- and weighted -‡- mean values considering the river drainage
982 surface, with the upper Drava excluded in the latter calculation) correspond to the main
983 sediment sources of the Danube watershed. Note that the weighted mean clay mineralogy of
984 these clusters (*i.e.* Alps + Dinarides + Carpathians) is close to that obtained for the Danube
985 River mainstream.

986 **REFERENCES**

- 987
- 988 Aksu, A.E., Hiscott, R.N., Kaminski, M.A., Mudie, P.J., Gillespie, H., Abrajano, T., Yaşar,
989 D., 2002. Last glacial–Holocene paleoceanography of the Black Sea and Marmara
990 Sea: stable isotopic, foraminiferal and coccolith evidence. *Mar. Geol.* 190, 119–149.
991 [https://doi.org/10.1016/S0025-3227\(02\)00345-6](https://doi.org/10.1016/S0025-3227(02)00345-6)
- 992 Árkai, P., 1991. Chlorite crystallinity: an empirical approach and correlation with illite
993 crystallinity, coal rank and mineral facies as exemplified by Palaeozoic and Mesozoic
994 rocks of northeast Hungary. *Journal of metamorphic Geology* 9, 723–734.
995 <https://doi.org/10.1111/j.1525-1314.1991.tb00561.x>
- 996 Árkai, P., Faryad, S.W., Vidal, O., Balogh, K., 2003. Very low-grade metamorphism of
997 sedimentary rocks of the Meliata unit, Western Carpathians, Slovakia: implications of
998 phyllosilicate characteristics. *International Journal of Earth Sciences* 92, 68–85.
999 <https://doi.org/10.1007/s00531-002-0303-x>
- 1000 Asch, K., Bellenberg, S., Commission for geological Map of the World, 2005. The 1: 5 million
1001 international geological map of Europe and adjacent areas (IGME 5000).
1002 Bundesanstalt für Geowissenschaften und Rohstoffe.
- 1003 Badertscher, S., Fleitmann, D., Cheng, H., Edwards, R.L., Göktürk, O.M., Zumbühl, A.,
1004 Leuenberger, M., Tüysüz, O., 2011. Pleistocene water intrusions from the
1005 Mediterranean and Caspian seas into the Black Sea. *Nat. Geosci.* 4 (4), 236-239.
1006 <https://doi.org/10.1038/NGEO1106>
- 1007 Bahr, A., Arz, H.W., Lamy, F., Wefer, G., 2006. Late glacial to Holocene paleoenvironmental
1008 evolution of the Black Sea, reconstructed with stable oxygen isotope records obtained
1009 on ostracod shells. *Earth Planet. Sci. Lett.* 241 (3-4), 863-875.
1010 <https://doi.org/10.1016/j.epsl.2005.10.036>
- 1011 Bahr, A., Lamy, F., Arz, H., Kuhlmann, H., Wefer, G., 2005. Late glacial to Holocene climate
1012 and sedimentation history in the NW Black Sea. *Mar. Geol.* 214 (4), 309-322.
1013 <https://doi.org/10.1016/j.margeo.2004.11.013>
- 1014 Bahr, A., Lamy, F., Arz, H.W., Major, C., Kwiecien, O., Wefer, G., 2008. Abrupt changes of
1015 temperature and water chemistry in the late Pleistocene and early Holocene Black Sea.
1016 *Geochem. Geophys. Geosyst.* 9. <https://doi.org/10.1029/2007GC001683>
- 1017 Bard, E., Rostek, F., Turon, J.-L., Gendreau, S., 2000. Hydrological impact of Heinrich events
1018 in the subtropical northeast Atlantic. *Science* 289, 1321–1324.
1019 <https://doi.org/10.1126/science.289.5483.1321>
- 1020 Bard, E., Rostek, F., Ménot-Combes, G., 2004. Radiocarbon calibration beyond 20,000 ¹⁴C
1021 yr BP by means of planktonic foraminifera of the Iberian Margin. *Quat. Res.* 61(2),
1022 204-214. <https://doi.org/10.1016/j.yqres.2003.11.006>
- 1023 Bard, E., Ménot, G., Rostek, F., Licari, L., Böning, P., Edwards, R. L., Cheng, H., Wang, Y.,
1024 Heaton, T. J., 2013. Radiocarbon calibration/comparison records based on marine
1025 sediments from the Pakistan and Iberian margins. *Radiocarbon*, 55(4), 1999-2019.
1026 https://doi.org/10.2458/azu_js_rc.55.17114
- 1027 Barker, S., Diz, P., Vautravers, M.J., Pike, J., Knorr, G., Hall, I.R., Broecker, W.S., 2009.
1028 Interhemispheric Atlantic seesaw response during the last deglaciation. *Nature* 457
1029 (7233), 1097. <https://doi.org/10.1038/nature07770>

- 1030 Barker, S., Knorr, G., Edwards, R. L., Parrenin, F., Putnam, A. E., Skinner, L. C., Wolff, E.,
1031 Ziegler, M., 2011. 800,000 years of abrupt climate variability. *Science*, 334 (6054),
1032 347-351. <https://doi.org/10.1126/science.1203580>
- 1033 Bayon, G., Barrat, J.A., Etoubleau, J., Benoit, M., Bollinger, C., Révillon, S., 2009.
1034 Determination of rare earth elements, Sc, Y, Zr, Ba, Hf and Th in geological samples
1035 by ICP-MS after Tm addition and alkaline fusion. *Geostandards and Geoanalytical*
1036 *Research* 33, 51–62. <https://doi.org/10.1111/j.1751-908X.2008.00880.x>
- 1037 Bayon, G., German, C.R., Boella, R.M., Milton, J.A., Taylor, R.N., Nesbitt, R.W., 2002. An
1038 improved method for extracting marine sediment fractions and its application to Sr
1039 and Nd isotopic analysis. *Chem. Geol.* 187, 179–199. [https://doi.org/10.1016/S0009-](https://doi.org/10.1016/S0009-2541(01)00416-8)
1040 [2541\(01\)00416-8](https://doi.org/10.1016/S0009-2541(01)00416-8)
- 1041 Bayon, G., Toucanne, S., Skonieczny, C., André, L., Bermell, S., Cheron, S., Dennielou, B.,
1042 Etoubleau, J., Freslon, N., Gauchery, T., Germain, Y., Jorry, S.J., Ménot, G., Monin,
1043 L., Ponzevera, E., Rouget, M.-L., Tachikawa, K., Barrat, J.A., 2015. Rare earth
1044 elements and neodymium isotopes in world river sediments revisited. *Geochimica et*
1045 *Cosmochimica Acta* 170, 17–38. <https://doi.org/10.1016/j.gca.2015.08.001>
- 1046 Becker, P., Seguinot, J., Jouvet, G., Funk, M., 2016. Last Glacial Maximum precipitation
1047 pattern in the Alps inferred from glacier modelling. *Geographica Helvetica* 71, 173–
1048 187. <https://doi.org/10.5194/gh-71-173-2016>
- 1049 Beghin, P., Charbit, S., Dumas, C., Kageyama, M., Ritz, C., 2015. How might the North
1050 American ice sheet influence the northwestern Eurasian climate? *Clim. Past*
1051 *Discussions* 11, 1467–1490. <https://doi.org/10.5194/cp-11-1467-2015>
- 1052 Blöschl, G., Nester, T., Komma, J., Parajka, J., Perdigão, R.A., 2013. The June 2013 flood in
1053 the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods.
1054 *Hydrology and Earth System Sciences* 17, 5197–5212. [https://doi.org/10.5194/hess-](https://doi.org/10.5194/hess-17-5197-2013)
1055 [17-5197-2013](https://doi.org/10.5194/hess-17-5197-2013)
- 1056 Blum, M.D., Törnqvist, T.E., 2000. Fluvial responses to climate and sea-level change: a
1057 review and look forward. *Sedimentology* 47, 2–48. [https://doi.org/10.1046/j.1365-](https://doi.org/10.1046/j.1365-3091.2000.00008.x)
1058 [3091.2000.00008.x](https://doi.org/10.1046/j.1365-3091.2000.00008.x)
- 1059 Bobos, I., 2012. Characterization of smectite to NH₄-illite conversion series in the fossil
1060 hydrothermal system of Harghita Băi, East Carpathians, Romania. *American*
1061 *Mineralogist* 97, 962–982. <https://doi.org/10.2138/am.2012.3801>
- 1062 Bonneau, L., Jorry, S.J., Toucanne, S., Silva Jacinto, R., Emmanuel, L., 2014. Millennial-
1063 scale response of a western Mediterranean river to late Quaternary climate changes: a
1064 view from the deep sea. *J. Geol.* 122, 687–703. <https://doi.org/10.1086/677844>
- 1065 Bonneau, L., Toucanne, S., Bayon, G., Jorry, S.J., Emmanuel, L., Jacinto, R.S., 2017. Glacial
1066 erosion dynamics in a small mountainous watershed (Southern French Alps): A
1067 source-to-sink approach. *Earth Planet. Sci. Lett.* 458, 366–379.
1068 <https://doi.org/10.1016/j.epsl.2016.11.004>
- 1069 Boswell, S.M., Toucanne, S., Creyts, T.T., Hemming, S.R., 2018. Continental-scale transport
1070 of sediments by the Baltic Ice Stream elucidated by coupled grain size and Nd
1071 provenance analyses. *Earth Planet. Sci. Lett.* 490, 143–150.
1072 <https://doi.org/10.1016/j.epsl.2018.03.017>

- 1073 Boswell, S.M., Toucanne, S., Pitel-Roudaut, M., Creyts, T.T., Eynaud, F., Bayon, G., 2019.
1074 Enhanced surface melting of the Fennoscandian Ice Sheet during periods of North
1075 Atlantic cooling. *Geology* 47 (7), 664-668. <https://doi.org/10.1130/G46370.1>
- 1076 Bousquet, R., Oberhänsli, R., Goffé, B., Wiederkehr, M., Koller, F., Schmid, S.M., Schuster,
1077 R., Engi, M., Berger, A., Martinotti, G., 2008. Metamorphism of metasediments at the
1078 scale of an orogen: a key to the Tertiary geodynamic evolution of the Alps. *Geological*
1079 *Society, London, Special Publications* 298, 393-411.
1080 <https://doi.org/10.1144/SP298.18>
- 1081 Bromley, G., Putnam, A., Borns, H., Lowell, T., Sandford, T., Barrell, D., 2018. Interstadial
1082 Rise and Younger Dryas Demise of Scotland's Last Ice Fields. *Paleoceanography and*
1083 *Paleoclimatology* 33, 412-429. <https://doi.org/10.1002/2018PA003341>
- 1084 Bronk Ramsey, C., 2001. Development of the Radiocarbon Calibration Program. *Radiocarbon*
1085 43, 355-363. <https://doi.org/10.1017/S0033822200038212>
- 1086 Bronk Ramsey, C., 2008. Deposition models for chronological records. *Quat. Sci. Rev.*, 27 (1-
1087 2), 42-60. <https://doi.org/10.1016/j.quascirev.2007.01.019>
- 1088 Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon*, 51 (1), 337-
1089 360. <https://doi.org/10.1017/S0033822200033865>
- 1090 Bronk Ramsey, C., 2017. Methods for summarizing radiocarbon datasets. *Radiocarbon*, 59
1091 (6), 1809-1833. <https://doi.org/10.1017/RDC.2017.108>
- 1092 Bronk Ramsey, C., Lee, S., 2013. Recent and Planned Developments of the Program OxCal.
1093 *Radiocarbon* 55, 720-730. <https://doi.org/10.1017/S0033822200057878>
- 1094 Brown, P.A., Kennett, J.P., 1998. Megaflood erosion and meltwater plumbing changes during
1095 last North American deglaciation recorded in Gulf of Mexico sediments. *Geology* 26,
1096 599-602. [https://doi.org/10.1130/0091-7613\(1998\)026<0599:MEAMPC>2.3.CO;2](https://doi.org/10.1130/0091-7613(1998)026<0599:MEAMPC>2.3.CO;2)
- 1097 Busschers, F.S., Kasse, C., Van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T.,
1098 Wallinga, J., Johns, C., Cleveringa, P., Bunnik, F.P.M., 2007. Late Pleistocene
1099 evolution of the Rhine-Meuse system in the southern North Sea basin: imprints of
1100 climate change, sea-level oscillation and glacio-isostasy. *Quat. Sci. Rev.* 26, 3216-
1101 3248. <https://doi.org/10.1016/j.quascirev.2007.07.013>
- 1102 Carlson, A.E., Clark, P.U., 2012. Ice sheet sources of sea level rise and freshwater discharge
1103 during the last deglaciation. *Rev. Geophys.* 50. <http://doi.org/10.1029/2011RG000371>
- 1104 Chaline, J., Jerz, H., 1984. Arbeitsergebnisse der Subkommission für Europäische
1105 Quartärstratigraphie. Stratotypen des Würm-Glazials. *Eiszeitalter und Gegenwart* 35,
1106 185-206.
- 1107 Chamley, H., 1989. *Clay sedimentology*, Springer-Verlag. ed. New York.
- 1108 Ciulavu, M., Mählmann, R.F., Schmid, S.M., Hofmann, H., Seghedi, A., Frey, M., 2008.
1109 Metamorphic evolution of a very low-to low-grade metamorphic core complex
1110 (Danubian window) in the South Carpathians. *Geological Society, London, Special*
1111 *Publications* 298, 281-315. <https://doi.org/10.1144/SP298.14>
- 1112 Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X.,
1113 Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. *Science* 325, 710-
1114 714. <https://doi.org/10.1126/science.1172873>

- 1115 Comiti, F., Mao, L., Penna, D., Dell'Agnes, A., Engel, M., Rathburn, S., Cavalli, M., 2019.
1116 Glacier melt runoff controls bedload transport in Alpine catchments. *Earth and*
1117 *Planet.Sci. Lett.* 520, 77-86. <https://doi.org/10.1016/j.epsl.2019.05.031>
- 1118 Constantinescu, A.M., Toucanne, S., Dennielou, B., Jorry, S.J., Mulder, T., Lericolais, G.,
1119 2015. Evolution of the Danube Deep-Sea Fan since the Last Glacial Maximum: new
1120 insights into Black Sea water-level fluctuations. *Mar. Geol.* 367, 50–68.
1121 <https://doi.org/10.1016/j.margeo.2015.05.007>
- 1122 Coulthard, T.J., Lewin, J., Macklin, M.G., 2005. Modelling differential catchment response to
1123 environmental change. *Geomorphology* 69, 222–241.
1124 <https://doi.org/10.1016/j.geomorph.2005.01.008>
- 1125 Covault, J.A., Romans, B.W., Graham, S.A., Fildani, A., Hilley, G.E., 2011. Terrestrial
1126 source to deep-sea sink sediment budgets at high and low sea levels: Insights from
1127 tectonically active Southern California. *Geology* 39, 619–622.
1128 <https://doi.org/10.1130/G31801.1>
- 1129 de Leeuw, A., Morton, A., van Baak, C.G.C., Vincent, S.J., 2018. Timing of arrival of the
1130 Danube to the Black Sea: Provenance of sediments from DSDP site 380/380A. *Terra*
1131 *Nova* 30, 114–124. <https://doi.org/10.1111/ter.12314>
- 1132 Dean, W.E., Arthur, M.A., 2011. Geochemical characteristics of Holocene laminated sapropel
1133 (unit II) and underlying lacustrine unit III in the Black Sea (Report n°. 2010–1323),
1134 Open-File Report. <https://doi.org/10.3133/ofr20101323>
- 1135 Debret, M., Copard, Y., Van Exem, A., Bessereau, G., Haeseler, F., Rouzaud, J.N., 2018. The
1136 color of refractory organic carbon. *Bulletin de la Société Géologique de France* 189
1137 (2), 9. <https://doi.org/10.1051/bsgf/2018008>
- 1138 Degens, E.T., Ross, D.A., 1972. Chronology of the Black Sea over the last 25,000 years.
1139 *Chem. Geol.* 10, 1–16. [https://doi.org/10.1016/0009-2541\(72\)90073-3](https://doi.org/10.1016/0009-2541(72)90073-3)
- 1140 Degens, E.T., Stoffers, P., Golubic, S., 1978. Varve chronology: Estimated rates of
1141 sedimentation in the Black Sea Basin. In D. A. Ross (Ed.), *Initial report of the deep*
1142 *sea drilling project* (Vol. 42, Part 2, pp. 499–508). Washington, D.C.: U.S.
1143 Government Printing Office.
- 1144 Deuser, W.G., 1972. Late Pleistocene and Holocene history of the Black Sea as indicated by
1145 stable isotope studies. *J. Geophys. Res.* 77, 1071–1077.
- 1146 Dypvik, H., Harris, N.B., 2001. Geochemical facies analysis of fine-grained siliciclastics
1147 using Th/U, Zr/Rb and (Zr+Rb)/Sr ratios. *Chem. Geol.* 181, 131-146.
1148 [https://doi.org/10.1016/S0009-2541\(01\)00278-9](https://doi.org/10.1016/S0009-2541(01)00278-9)
- 1149 Eglinton, T.I., Benitez-Nelson, B.C., Pearson, A., McNichol, A.P., Bauer, J.E., Druffel, E.R.,
1150 1997. Variability in radiocarbon ages of individual organic compounds from marine
1151 sediments. *Science* 277, 796–799. <https://doi.org/10.1126/science.277.5327.796>
- 1152 Ehlers, J., Gibbard, P.L., 2004. Quaternary glaciations-extent and chronology: part I: Europe.
1153 Elsevier.
- 1154 Ellwanger, D., Wielandt-Schuster, U., Franz, M., Simon, T., 2011. The Quaternary of the
1155 southwest German Alpine Foreland (Bodensee-Oberschwaben, Baden-Württemberg,
1156 Southwest Germany). *Quat. Sci. J.* 60, 306–328. <https://doi.org/10.3285/eg.60.2-3.07>

- 1157 Fitzsimmons, K.E., Marković, S.B., Hambach, U., 2012. Pleistocene environmental dynamics
1158 recorded in the loess of the middle and lower Danube basin. *Quat. Sci. Rev.* 41, 104–
1159 118. <https://doi.org/10.1016/j.quascirev.2012.03.002>
- 1160 Florineth, D., Schlüchter, C., 2000. Alpine evidence for atmospheric circulation patterns in
1161 Europe during the Last Glacial Maximum. *Quat. Res.* 54, 295–308.
1162 <https://doi.org/10.1006/qres.2000.2169>
- 1163 Freymond, C.V., Peterse, F., Fischer, L.V., Filip, F., Giosan, L., Eglinton, T.I., 2017.
1164 Branched GDGT signals in fluvial sediments of the Danube River basin: Method
1165 comparison and longitudinal evolution. *Org. Geochem.* 103, 88–96.
1166 <https://doi.org/10.1016/j.orggeochem.2016.11.002>
- 1167 Frost, C.D., O’Nions, R.K., Goldstein, S.L., 1986. Mass balance for Nd in the Mediterranean
1168 Sea. *Chem. Geol.* 55, 45–50. [https://doi.org/10.1016/0009-2541\(86\)90126-9](https://doi.org/10.1016/0009-2541(86)90126-9)
- 1169 Gábris, G., Nádor, A., 2007. Long-term fluvial archives in Hungary: response of the Danube
1170 and Tisza rivers to tectonic movements and climatic changes during the Quaternary: a
1171 review and new synthesis. *Quat. Sci. Rev.* 26, 2758–2782.
1172 <https://doi.org/10.1016/j.quascirev.2007.06.030>
- 1173 Garnier, J., Billen, G., Hannon, E., Fonbonne, S., Videnina, Y., Soulie, M., 2002. Modelling
1174 the Transfer and Retention of Nutrients in the Drainage Network of the Danube River.
1175 *Estuarine, Coastal and Shelf Science* 54, 285–308.
1176 <https://doi.org/10.1006/ecss.2000.0648>
- 1177 Gibbard, P.L., 1988. The history of the great northwest European rivers during the past three
1178 million years. *Philosophical Transactions of the Royal Society of London. B, Biol.*
1179 *Sci.* 318, 559–602. <https://doi.org/10.1098/rstb.1988.0024>
- 1180 Giosan, L., Donnelly, J.P., Constantinescu, S., Filip, F., Ovejanu, I., Vespremeanu-Stroe, A.,
1181 Vespremeanu, E., Duller, G.A., 2006. Young Danube delta documents stable Black
1182 Sea level since the middle Holocene: Morphodynamic, paleogeographic, and
1183 archaeological implications. *Geology* 34, 757–760. <https://doi.org/10.1130/G22587.1>
- 1184 Giosan, L., Donnelly, J.P., Vespremeanu, E., Bhattacharya, J.P., Olariu, C., Buonaiuto, F.S.,
1185 2005. River delta morphodynamics: Examples from the Danube delta. L. Giosan, J.P.
1186 Bhattacharya (Eds.), *River Deltas - Concepts, Models and Examples*, SEPM Special
1187 Publication, 83 (2005), pp. 393-411.
- 1188 Glur, L., Wirth, S.B., Büntgen, U., Gilli, A., Haug, G.H., Schär, C., Beer, J., Anselmetti, F.S.,
1189 2013. Frequent floods in the European Alps coincide with cooler periods of the past
1190 2500 years. *Sci. Rep.* 3, 2770. <https://doi.org/10.1038/srep02770>
- 1191 Goldstein, S.J., Jacobsen, S.B., 1988. Nd and Sr isotopic systematics of river water suspended
1192 material: implications for crustal evolution. *Earth Planet. Sci. Lett.* 87, 249–265.
1193 [https://doi.org/10.1016/0012-821X\(88\)90013-1](https://doi.org/10.1016/0012-821X(88)90013-1)
- 1194 Goodbred Jr, S.L., Kuehl, S.A., 2000. Enormous Ganges-Brahmaputra sediment discharge
1195 during strengthened early Holocene monsoon. *Geology* 28, 1083–1086.
1196 [https://doi.org/10.1130/0091-7613\(2000\)28<1083:EGSDDS>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<1083:EGSDDS>2.0.CO;2)
- 1197 Gorlach, A., Hang, T., Kalm, V., 2017. GIS-based reconstruction of Late Weichselian
1198 proglacial lakes in northwestern Russia and Belarus. *Boreas* 46, 486–502.
1199 <https://doi.org/10.1111/bor.12223>

- 1200 Grosswald, M.G., 1980. Late Weichselian ice sheet of northern Eurasia. *Quaternary Research*
1201 13, 1–32. [https://doi.org/10.1016/0033-5894\(80\)90080-0](https://doi.org/10.1016/0033-5894(80)90080-0)
- 1202 Guichard, F., Carey, S., Arthur, M.A., Sigurdsson, H., Arnold, M., 1993. Tephra from the
1203 Minoan eruption of Santorini in sediments of the Black Sea. *Nature* 363, 610.
1204 <https://doi.org/10.1038/363610a0>
- 1205 Habbe, K.A., Rögner, K., 1989. The Pleistocene Iller Glaciers and their outwash fields.
1206 *Catena Supplement* 15, 311–328.
- 1207 Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. *Annals*
1208 *of Glaciology* 4, 85–90. <https://doi.org/10.3189/S026030550000528>
- 1209 Hallet, B., Hunter, L., Bogen, J., 1996. Rates of erosion and sediment evacuation by glaciers:
1210 A review of field data and their implications. *Glob. Planet. Chang.*12, 213–235.
1211 [https://doi.org/10.1016/0921-8181\(95\)00021-6](https://doi.org/10.1016/0921-8181(95)00021-6)
- 1212 Heaton, T. J., Bard, E., & Hughen, K. A., 2013. Elastic tie-pointing-transferring chronologies
1213 between records via a Gaussian process. *Radiocarbon*, 55(4), 1975-1997.
1214 https://doi.org/10.2458/azu_js_rc.55.17777
- 1215 Heiri, O., Koinig, K.A., Spötl, C., Barrett, S., Brauer, A., Drescher-Schneider, R., Gaar, D.,
1216 Ivy-Ochs, S., Kerschner, H., Luetscher, M., 2014. Palaeoclimate records 60–8 ka in
1217 the Austrian and Swiss Alps and their forelands. *Quat. Sci. Rev.* 106, 186–205.
1218 <https://doi.org/10.1016/j.quascirev.2014.05.021>
- 1219 Hemming, S.R., 2004. Heinrich events: Massive late Pleistocene detritus layers of the North
1220 Atlantic and their global climate imprint. *Rev. Geophys.* 42.
1221 <https://doi.org/10.1029/2003RG000128>
- 1222 Henry, F., Jeandel, C., Dupre, B., Minster, J.-F., 1994. Particulate and dissolved Nd in the
1223 western Mediterranean Sea: sources, fate and budget. *Mar. Chem.* 45, 283–305.
1224 [https://doi.org/10.1016/0304-4203\(94\)90075-2](https://doi.org/10.1016/0304-4203(94)90075-2)
- 1225 Hinderer, M., 2001. Late Quaternary denudation of the Alps, valley and lake fillings and
1226 modern river loads. *Geodinamica Acta* 14, 231–263.
1227 <https://doi.org/10.1080/09853111.2001.11432446>
- 1228 Hinderer, M., Kastowski, M., Kamelger, A., Bartolini, C., Schlunegger, F., 2013. River loads
1229 and modern denudation of the Alps: a review. *Earth. Sci. Rev.* 118, 11–44.
1230 <https://doi.org/10.1016/j.earscirev.2013.01.001>
- 1231 Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., 2016. The last
1232 Eurasian ice sheets - a chronological database and time-slice reconstruction, DATED-
1233 1. *Boreas* 45, 1–45. <https://doi.org/10.1111/bor.12142>
- 1234 Hughes, P.D., Woodward, J.C., Van Calsteren, P.C., Thomas, L.E., 2011. The glacial history
1235 of the Dinaric Alps, Montenegro. *Quat. Sci.Rev.* 30, 3393–3412.
1236 <https://doi.org/10.1016/j.quascirev.2011.08.016>
- 1237 Huybers, P., 2006. Early Pleistocene glacial cycles and the integrated summer insolation
1238 forcing. *Science* 313, 508–511. <https://doi.org/10.1126/science.1125249>
- 1239 Ivy-Ochs, S., 2015. Glacier variations in the European Alps at the end of the last glaciation.
1240 *Cuadernos de Investigación Geográfica* 41, 295. <https://doi.org/10.18172/cig.2750>

- 1241 Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W.,
1242 Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. *J.*
1243 *Quat. Sci.* 23, 559–573. <https://doi.org/10.1002/jqs.1202>
- 1244 Ivy-Ochs, S., Lucchesi, S., Baggio, P., Fioraso, G., Gianotti, F., Monegato, G., Graf, A.A.,
1245 Akçar, N., Christl, M., Carraro, F., Forno, M.G., Schlüchter, C., 2018. New
1246 geomorphological and chronological constraints for glacial deposits in the Rivoli-
1247 Avigliana end-moraine system and the lower Susa Valley (Western Alps, NW Italy). *J.*
1248 *Quat. Sci.* 33, 550–562. <https://doi.org/10.1002/jqs.3034>
- 1249 Ivy-Ochs, S., Schäfer, J., Kubik, P.W., Synal, H.-A., Schlüchter, C., 2004. Timing of
1250 deglaciation on the northern Alpine foreland (Switzerland). *Eclogae Geologicae*
1251 *Helveticae* 97, 47–55.
- 1252 Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. *Earth Planet.*
1253 *Sci. Lett.* 50, 139–155. [https://doi.org/10.1016/0012-821X\(80\)90125-9](https://doi.org/10.1016/0012-821X(80)90125-9)
- 1254 Jacq, K., Perrette, Y., Fanget, B., Sabatier, P., Coquin, D., Martinez-Lamas, R., Debret, M.,
1255 Arnaud, F., 2019. High-resolution prediction of organic matter concentration with
1256 hyperspectral imaging on a sediment core. *Science of the Total Environment* 663,
1257 236–244. <https://doi.org/10.1016/j.scitotenv.2019.01.320>
- 1258 Jaeger, J.M., Koppes, M.N., 2016. The role of the cryosphere in source-to-sink systems. *Earth*
1259 *Sci. Rev.* 153, 43–76. <https://doi.org/10.1016/j.earscirev.2015.09.011>
- 1260 Jiao, R., Herman, F., Beyssac, O., Adatte, T., Cox, S.C., Nelson, F.E., Neil, H.L., 2018.
1261 Erosion of the Southern Alps of New Zealand during the last deglaciation. *Geology*
1262 46, 975–978. <https://doi.org/10.1130/G45160.1>
- 1263 Jones, G.A., Gagnon, A.R., 1994. Radiocarbon chronology of Black Sea sediments. *Deep-Sea*
1264 *Res. Part I: Oceanogr.* 41, 531–557. [https://doi.org/10.1016/0967-0637\(94\)90094-9](https://doi.org/10.1016/0967-0637(94)90094-9)
- 1265 Juteau, M., Michard, A., Albarede, F., 1986. The Pb-Sr-Nd isotope geochemistry of some
1266 recent circum-Mediterranean granites. *Contributions to Mineralogy and Petrology* 92,
1267 331–340.
- 1268 Karabanov, A.K., Matveyev, A.V., 2011. The Pleistocene glaciations in Belarus. *Quaternary*
1269 *Sciences*. Elsevier, pp. 29–35. <https://doi.org/10.1016/B978-0-444-53447-7.00003-9>
- 1270 Kasse, C., Bohncke, S.J.P., Vandenberghe, J., Gábris, G., 2010. Fluvial style changes during
1271 the last glacial–interglacial transition in the middle Tisza valley (Hungary).
1272 *Proceedings of the Geologists' Association* 121, 180–194.
1273 <https://doi.org/10.1016/j.pgeola.2010.02.005>
- 1274 Ker, S., Riboulot, V., 2015. GHASS cruise, R/V Pourquoi Pas?.
1275 <https://doi.org/10.17600/15000500>
- 1276 Kisch, H.J., 1991. Illite crystallinity: recommendations on sample preparation, X-ray
1277 diffraction settings, and interlaboratory samples. *Journal of Metamorphic Geology* 9,
1278 665–670. <https://doi.org/10.1111/j.1525-1314.1991.tb00556.x>
- 1279 Kiss, P., Gméling, K., Molnár, F., Pécskay, Z., 2010. Geochemistry of Sarmatian volcanic
1280 rocks in the Tokaj Mts (NE Hungary) and their relationship to hydrothermal
1281 mineralization. *Central European Geology* 53, 377–403.
1282 <https://doi.org/10.1556/CEuGeol.53.2010.4.3>
- 1283 Kolla, V., Perlmutter, M.A., 1993. Timing of turbidite sedimentation on the Mississippi Fan.
1284 *Aapg Bulletin* 77, 1129–1141.

- 1285 Krinsley, D.H., Donahue, J., 1968. Environmental interpretation of sand grain surface textures
1286 by electron microscopy. *GSA Bulletin* 79, 743–748. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1968)79[743:EIOSGS]2.0.CO;2)
1287 [7606\(1968\)79\[743:EIOSGS\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1968)79[743:EIOSGS]2.0.CO;2)
- 1288 Krumm, H., Petschick, R., Wolf, M., 1988. From diagenesis to anchimetamorphism, upper
1289 Austroalpine sedimentary cover in Bavaria and Tyrol. *Geodinamica Acta* 2, 33–47.
1290 <https://doi.org/10.1080/09853111.1988.11105154>
- 1291 Kubler, B., 1967. La cristallinité de l'illite et les zones tout à fait supérieures du
1292 métamorphisme. *Etages tectoniques* 105–121.
- 1293 Kusch, S., Rethemeyer, J., Schefuß, E., Mollenhauer, G., 2010. Controls on the age of
1294 vascular plant biomarkers in Black Sea sediments. *Geochimica et Cosmochimica Acta*
1295 74, 7031–7047. <https://doi.org/10.1016/j.gca.2010.09.005>
- 1296 Kwiecien, O., Arz, H.W., Lamy, F., Wulf, S., Bahr, A., Röhl, U., Haug, G.H., 2008.
1297 Estimated reservoir ages of the black sea since the last glacial. *Radiocarbon* 50, 99–
1298 118. <https://doi.org/10.1017/S0033822200043393>
- 1299 Larsen, N.K., Knudsen, K.L., Krohn, C.F., Kronborg, C., Murray, A.S., Nielsen, O.B., 2009.
1300 Late Quaternary ice sheet, lake and sea history of southwest Scandinavia—a synthesis.
1301 *Boreas* 38, 732–761. <https://doi.org/10.1111/j.1502-3885.2009.00101.x>
- 1302 Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-
1303 term numerical solution for the insolation quantities of the Earth. *Astronomy &*
1304 *Astrophysics* 428, 261–285. <https://doi.org/10.1051/0004-6361:20041335>
- 1305 Lehmann, B., Herman, F., Valla, P.G., King, G.E., Biswas, R.H., Ivy-Ochs, S., Steinemann,
1306 O., Christl, M., 2020. Postglacial erosion of bedrock surfaces and deglaciation timing:
1307 New insights from the Mont Blanc massif (western Alps). *Geology* 48.
1308 <https://doi.org/10.1130/G46585.1>
- 1309 Lericolais, G., 2004. ASSEMBLAGE-1 cruise, R/V Marion Dufresne.
1310 <https://doi.org/10.17600/4200070>
- 1311 Lericolais, G., Bourget, J., Popescu, I., Jermannaud, P., Mulder, T., Jorry, S., Panin, N., 2013.
1312 Late Quaternary deep-sea sedimentation in the western Black Sea: New insights from
1313 recent coring and seismic data in the deep basin. *Glob. Planet. Chang.* 103, 232–247.
1314 <https://doi.org/10.1016/j.gloplacha.2012.05.002>
- 1315 Lericolais, G., Guichard, F., Morigi, C., Popescu, I., Bulois, C., Gillet, H., Ryan, W.B.F.,
1316 2011. Assessment of Black Sea water-level fluctuations since the Last Glacial
1317 Maximum. *Geology and Geoarchaeology of the Black Sea Region: Beyond the Flood*
1318 *Hypothesis* 473, 33.
- 1319 Ludwig, P., Schaffernicht, E.J., Shao, Y., Pinto, J.G., 2016. Regional atmospheric circulation
1320 over Europe during the Last Glacial Maximum and its links to precipitation. *Journal of*
1321 *Geophysical Research: Atmospheres* 121, 2130–2145.
1322 <https://doi.org/10.1002/2015JD024444>
- 1323 Luetscher, M., Boch, R., Sodemann, H., Spötl, C., Cheng, H., Edwards, R.L., Frisia, S., Hof,
1324 F., Müller, W., 2015. North Atlantic storm track changes during the Last Glacial
1325 Maximum recorded by Alpine speleothems. *Nature Com.* 6.
1326 <https://doi.org/10.1038/ncomms7344>

- 1327 Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Michczyńska, D.J., Soja,
1328 R., Starkel, L., Thorndycraft, V.R., 2006. Past hydrological events reflected in the
1329 Holocene fluvial record of Europe. *Catena* 66, 145–154.
1330 <https://doi.org/10.1016/j.catena.2005.07.015>
- 1331 Macklin, M.G., Johnstone, E., Lewin, J., 2005. Pervasive and long-term forcing of Holocene
1332 river instability and flooding in Great Britain by centennial-scale climate change. *The*
1333 *Holocene* 15, 937–943. <https://doi.org/10.1191/0959683605hl867ft>
- 1334 Macklin, M.G., Lewin, J., 2003. River sediments, great floods and centennial-scale Holocene
1335 climate change. *J. Quat. Sci.* 18, 101–105. <https://doi.org/10.1002/jqs.751>
- 1336 Macklin, M.G., Lewin, J., Woodward, J.C., 2012. The fluvial record of climate change.
1337 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
1338 *Engineering Sciences* 370, 2143–2172. <https://doi.org/10.1098/rsta.2011.0608>
- 1339 Magyari, E. K., Pál, I., Vincze, I., Veres, D., Jakab, G., Braun, M., Szalai, Z., Szabo, Z.,
1340 Korponai, J., 2019. Warm Younger Dryas summers and early late glacial spread of
1341 temperate deciduous trees in the Pannonian Basin during the last glacial termination
1342 (20-9 kyr cal BP). *Quat. Sci. Rev.*, 225, 105980.
1343 <https://doi.org/10.1016/j.quascirev.2019.105980>
- 1344 Major, C., Ryan, W., Lericolais, G., Hajdas, I., 2002. Constraints on Black Sea outflow to the
1345 Sea of Marmara during the last glacial–interglacial transition. *Mar. Geol.* 190 (1-2),
1346 19–34. [https://doi.org/10.1016/S0025-3227\(02\)00340-7](https://doi.org/10.1016/S0025-3227(02)00340-7)
- 1347 Major, C.O., Goldstein, S.L., Ryan, W.B., Lericolais, G., Piotrowski, A.M., Hajdas, I., 2006.
1348 The co-evolution of Black Sea level and composition through the last deglaciation and
1349 its paleoclimatic significance. *Quat. Sci. Rev.* 25, 2031–2047.
1350 <https://doi.org/10.1016/j.quascirev.2006.01.032>
- 1351 Makos, M., Dzierżek, J., Nitychoruk, J., Zreda, M., 2014. Timing of glacier advances and
1352 climate in the High Tatra Mountains (Western Carpathians) during the Last Glacial
1353 Maximum. *Quat. Res.* 82, 1–13. <https://doi.org/10.1016/j.yqres.2014.04.001>
- 1354 Makos, M., Nitychoruk, J., Zreda, M., 2013. Deglaciation chronology and paleoclimate of the
1355 Pięciu Stawów Polskich/Roztoki Valley, high Tatra Mountains, Western Carpathians,
1356 since the Last Glacial Maximum, inferred from ³⁶Cl exposure dating and glacier–
1357 climate modelling. *Quat. Int.* 293, 63–78. <https://doi.org/10.1016/j.quaint.2012.01.016>
- 1358 Makos, M., Rinterknecht, V., Braucher, R., Tołoczko-Pasek, A., Arnold, M., Aumaître, G.,
1359 Bourlès, D., Keddadouche, K., 2018. Last Glacial Maximum and Lateglacial in the
1360 Polish High Tatra Mountains - Revised deglaciation chronology based on the 10 Be
1361 exposure age dating. *Quat. Sci. Rev.* 187, 130–156.
1362 <https://doi.org/10.1016/j.quascirev.2018.03.006>
- 1363 Makshaev, R.R., Svitoch, A.A., 2016. Chocolate clays of the Northern Caspian Sea Region:
1364 Distribution, structure, and origin. *Quat. Int.* 409, 44–49.
1365 <https://doi.org/10.1016/j.quaint.2015.07.018>
- 1366 Mangerud, J., Jakobsson, M., Alexanderson, H., Astakhov, V., Clarke, G.K., Henriksen, M.,
1367 Hjort, C., Krinner, G., Lunkka, J.-P., Möller, P., 2004. Ice-dammed lakes and
1368 rerouting of the drainage of northern Eurasia during the Last Glaciation. *Quat. Sci.*
1369 *Rev.* 23, 1313–1332. <https://doi.org/10.1016/j.quascirev.2003.12.009>

- 1370 Marković, S.B., Stevens, T., Kukla, G.J., Hambach, U., Fitzsimmons, K.E., Gibbard, P.,
1371 Buggle, B., Zech, M., Guo, Z., Hao, Q., Wu, H., O'Hara Dhand, K., Smalley, I.J.,
1372 Újvári, G., Sümegei, P., Timar-Gabor, A., Veres, D., Sirocko, F., Vasiljević, D.A., Jary,
1373 Z., Svensson, A., Jović, V., Lehmkuhl, F., Kovács, J., Svirčev, Z., 2015. Danube loess
1374 stratigraphy - Towards a pan-European loess stratigraphic model. *Earth Sci. Rev.* 148,
1375 228–258. <https://doi.org/10.1016/j.earscirev.2015.06.005>
- 1376 Marret, F., Mudie, P., Aksu, A., Hiscott, R. N., 2009. A Holocene dinocyst record of a two-
1377 step transformation of the Neoeuxinian brackish water lake into the Black Sea. *Quat.*
1378 *Int.* 197(1-2), 72-86. <https://doi.org/10.1016/j.quaint.2007.01.010>
- 1379 Matenco, L., Andriessen, P., 2013. Quantifying the mass transfer from mountain ranges to
1380 deposition in sedimentary basins: Source to sink studies in the Danube Basin–Black
1381 Sea system. *Glob. Planet. Chang.* 103, 1–18.
1382 <https://doi.org/10.1016/j.gloplacha.2013.01.003>
- 1383 Mayr, C., Stojakowits, P., Lempe, B., Blaauw, M., Diersche, V., Grohgan, M., Correa, M.L.,
1384 Ohlendorf, C., Reimer, P., Zolitschka, B., 2019. High-resolution geochemical record
1385 of environmental changes during MIS 3 from the northern Alps (Nesseltalgraben,
1386 Germany). *Quat. Sci. Rev.* 218, 122–136.
1387 <https://doi.org/10.1016/j.quascirev.2019.06.013>
- 1388 Ménot, G., Bard, E., Rostek, F., Weijers, J.W., Hopmans, E.C., Schouten, S., Damsté, J.S.S.,
1389 2006. Early reactivation of European rivers during the last deglaciation. *Science* 313,
1390 1623–1625. <https://doi.org/10.1126/science.1130511>
- 1391 Milliman, J.D., Farnsworth, K.L., 2013. River discharge to the coastal ocean: a global
1392 synthesis. Cambridge University Press.
- 1393 Milliman, J.D., Syvitski, J.P., 1992. Geomorphic/tectonic control of sediment discharge to the
1394 ocean: the importance of small mountainous rivers. *J. Geol.* 100, 525–544.
1395 <https://doi.org/10.1086/629606>
- 1396 Misch, D., Wegerer, E., Gross, D., Sachsenhofer, R.F., Rachetti, A., Gratzer, R., 2018.
1397 Mineralogy and facies variations of Devonian and Carboniferous shales in the
1398 Ukrainian Dniepr-Donets Basin. *Aust. J. Earth. Sci.* 111, 15–25.
1399 <https://doi.org/10.17738/ajes.2018.0002>
- 1400 Mol, J., Vandenberghe, J., Kasse, C., 2000. River response to variations of periglacial climate
1401 in mid-latitude Europe. *Geomorphology* 33, 131–148. [https://doi.org/10.1016/S0169-555X\(99\)00126-9](https://doi.org/10.1016/S0169-555X(99)00126-9)
- 1403 Monegato, G., Ravazzi, C., Donegana, M., Pini, R., Calderoni, G., Wick, L., 2007. Evidence
1404 of a two-fold glacial advance during the last glacial maximum in the Tagliamento end
1405 moraine system (eastern Alps). *Quat. Res.* 68, 284–302.
1406 <https://doi.org/10.1016/j.yqres.2007.07.002>
- 1407 Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., Piccin, A., 2017. The Alpine LGM in the
1408 boreal ice-sheets game. *Sci. Rep.* 7, 2078. <https://doi.org/10.1038/s41598-017-02148-7>
- 1410 Mulder, T., Alexander, J., 2001. The physical character of subaqueous sedimentary density
1411 flows and their deposits. *Sedimentology* 48, 269–299. <https://doi.org/10.1046/j.1365-3091.2001.00360.x>
- 1412

- 1413 Mulder, T., Syvitski, J.P., 1995. Turbidity currents generated at river mouths during
1414 exceptional discharges to the world oceans. *J. Geol.* 103, 285–299.
1415 <https://doi.org/10.1086/629747>
- 1416 Mulder, T., Syvitski, J.P., Migeon, S., Faugeres, J.-C., Savoye, B., 2003. Marine hyperpycnal
1417 flows: initiation, behavior and related deposits. A review. *Mar. Pet. Geol.* 20, 861–
1418 882. <https://doi.org/10.1016/j.marpetgeo.2003.01.003>
- 1419 Mulder, T., Syvitski, J.P., Skene, K.I., 1998. Modeling of erosion and deposition by turbidity
1420 currents generated at river mouths. *J. Sedim. Res.* 68, 124–137.
1421 <https://doi.org/10.2110/jsr.68.124>
- 1422 Müller, G., Quakernaat, J., 1969. Diffractometric clay mineral analysis of recent sediments of
1423 Lake Constance (Central Europe). *Contributions to Mineralogy and Petrology* 22,
1424 268–275.
- 1425 Muttoni, G., Carcano, C., Garzanti, E., Ghielmi, M., Piccin, A., Pini, R., Rogledi, S.,
1426 Sciunnach, D., 2003. Onset of major Pleistocene glaciations in the Alps. *Geology* 31,
1427 989–992. <https://doi.org/10.1130/G19445.1>
- 1428 NGRIP-members, 2004. High resolution record of Northern Hemisphere climate extending
1429 into the last interglacial period. *Nature* 431, 147–151.
1430 <https://doi.org/10.1038/nature02805>
- 1431 Nievergelt, P., Liniger, M., Froitzheim, N., Mählmann, R.F., 1996. Early to mid-Tertiary
1432 crustal extension in the Central Alps: The Turba mylonite zone (eastern Switzerland).
1433 *Tectonics* 15, 329–340. <https://doi.org/10.1029/93TC02312>
- 1434 Nikishin, A.M., Korotaev, M.V., Ershov, A.V., Brunet, M.-F., 2003. The Black Sea basin:
1435 tectonic history and Neogene–Quaternary rapid subsidence modelling.
1436 *Sedim. Geol.* 156, 149–168. [https://doi.org/10.1016/S0037-0738\(02\)00286-5](https://doi.org/10.1016/S0037-0738(02)00286-5)
- 1437 Normark, W.R., Piper, D.J., 1991. Initiation processes and flow evolution of turbidity
1438 currents: implications for the depositional record. *SEPM Special Publications*, 46,
1439 207–230
- 1440 Oerlemans, J., Greuell, W., Denby, B., van de Wal, R., 2001. 10 years of mass-balance
1441 measurements along a transect near Kangerlussuaq, central West Greenland. *Journal*
1442 *of Glaciology* 47, 157–158. <https://doi.org/10.3189/172756501781832458>
- 1443 Panin, N., Jipa, D., 2002. Danube River sediment input and its interaction with the north-
1444 western Black Sea. *Estuar. Coast. Shelf Sci.* 54, 551–562.
1445 <https://doi.org/10.1006/ecss.2000.0664>
- 1446 Panin, N., Panin, S., Herz, N., Noakes, J.E., 1983. Radiocarbon dating of Danube delta
1447 deposits. *Quat. Res.* 19, 249–255. [https://doi.org/10.1016/0033-5894\(83\)90008-X](https://doi.org/10.1016/0033-5894(83)90008-X)
- 1448 Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., Cheval, S., Dumitrescu,
1449 A., Gaume, E., Hlavčová, K., 2010. Seasonal characteristics of flood regimes across
1450 the Alpine–Carpathian range. *J. Hydrol.* 394, 78–89.
1451 <https://doi.org/10.1016/j.jhydrol.2010.05.015>
- 1452 Pastre, J.-F., Limondin-Lozouet, N., Leroyer, C., Ponel, P., Fontugne, M., 2003. River system
1453 evolution and environmental changes during the Lateglacial in the Paris Basin
1454 (France). *Quat. Sci. Rev.* 22, 2177–2188. [https://doi.org/10.1016/S0277-3791\(03\)00147-1](https://doi.org/10.1016/S0277-3791(03)00147-1)
1455

- 1456 Pellegrini, C., Asioli, A., Bohacs, K.M., Drexler, T.M., Feldman, H.R., Sweet, M.L., Maselli,
1457 V., Rovere, M., Gamberi, F., Dalla Valle, G., 2018. The late Pleistocene Po River
1458 lowstand wedge in the Adriatic Sea: Controls on architecture variability and sediment
1459 partitioning. *Mar. Pet. Geol.* 96, 16–50.
1460 <https://doi.org/10.1016/j.marpetgeo.2018.03.002>
- 1461 Pellegrini, C., Maselli, V., Gamberi, F., Asioli, A., Bohacs, K.M., Drexler, T.M., Trincardi,
1462 F., 2017. How to make a 350-m-thick lowstand systems tract in 17,000 years: The
1463 Late Pleistocene Po River (Italy) lowstand wedge. *Geology* 45, 327–330.
1464 <https://doi.org/10.1130/G38848.1>
- 1465 Piper, D.J., Normark, W.R., 2009. Processes that initiate turbidity currents and their influence
1466 on turbidites: a marine geology perspective. *J. Sedim. Res.* 79, 347–362.
1467 <https://doi.org/10.2110/jsr.2009.046>
- 1468 Popescu, I., Lericolais, G., Panin, N., Normand, A., Dinu, C., Le Drezen, E., 2004. The
1469 Danube submarine canyon (Black Sea): Morphology and sedimentary processes. *Mar.*
1470 *Geol.* 206 (1-4), 249-265. <https://doi.org/10.1016/j.margeo.2004.03.003>
- 1471 Popescu, I., Lericolais, G., Panin, N., Wong, H.K., Droz, L., 2001. Late Quaternary channel
1472 avulsions on the Danube deep-sea fan, Black Sea. *Mar. Geol.* 179, 25–37.
1473 [https://doi.org/10.1016/S0025-3227\(01\)00197-9](https://doi.org/10.1016/S0025-3227(01)00197-9)
- 1474 Preusser, F., 2004. Towards a chronology of the Late Pleistocene in the northern Alpine
1475 Foreland. *Boreas* 33, 195–210. <https://doi.org/10.1111/j.1502-3885.2004.tb01141.x>
- 1476 Preusser, F., Graf, H.R., Keller, O., Krayss, E., Schlüchter, C., 2011. Quaternary glaciation
1477 history of northern Switzerland. *Quat. Sci. J.* 60, 282–305.
1478 <https://doi.org/10.3285/eg.60.2-3.06>
- 1479 Rainer, T., Herlec, U., Rantitsch, G., Sachsenhofer, R.F., Vrabec, M., 2002. Organic matter
1480 maturation vs clay mineralogy: A comparison for Carboniferous to Eocene sediments
1481 from the Alpine-Dinaride junction (Slovenia, Austria). *Geologija* 45, 513–518.
- 1482 Rantitsch, G., 1997. Thermal history of the Carnic Alps (Southern Alps, Austria) and its
1483 palaeogeographic implications. *Tectonophysics* 272, 213–232.
1484 [https://doi.org/10.1016/S0040-1951\(96\)00259-4](https://doi.org/10.1016/S0040-1951(96)00259-4)
- 1485 Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H.,
1486 Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., Fisher, H., Gkinis, V., Guillevic, M.,
1487 Hoek, W. Z., Lowe, J. J., Pedro, J. B., Poop, T., Walker, I. K., Wheatley, J. J.,
1488 Winstrup, M. 2014. A stratigraphic framework for abrupt climatic changes during the
1489 Last Glacial period based on three synchronized Greenland ice-core records: refining
1490 and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.*, 106, 14-28.
1491 <https://doi.org/10.1016/j.quascirev.2014.09.007>
- 1492 Ravazzi, C., Pini, R., Badino, F., De Amicis, M., Londeix, L., Reimer, P.J., 2014. The latest
1493 LGM culmination of the Garda Glacier (Italian Alps) and the onset of glacial
1494 termination. Age of glacial collapse and vegetation chronosequence. *Quat. Sci. Rev.*
1495 105, 26–47. <https://doi.org/10.1016/j.quascirev.2014.09.014>
- 1496 Reber, R., Akcar, N., Ivy-Ochs, S., Tikhomirov, D., Burkhalter, R., Zahno, C., Lüthold, A.,
1497 Kubik, P., Vockenhuber, C., Schlüchter, C., 2014. Deglaciation of the Reuss Glacier
1498 in the Alps at the end of the Last Glacial Maximum. *Swiss Journal of Geosciences*
1499 107, 293–307. <https://doi.org/10.1007/s00015-014-0169-5>

- 1500 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E.,
1501 Cheng, H., Edwards, R.L., Friedrich, M., 2013. IntCal13 and Marine13 radiocarbon
1502 age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55, 1869–1887.
1503 https://doi.org/10.2458/azu_js_rc.55.16947
- 1504 Reitner, J.M., 2012. Challenges in deciphering the Last Glacial Cycle in Eastern Alps:
1505 Examples from the Drau glacier system. *Quat. Int.* 279, 398.
1506 <https://doi.org/10.1016/j.quaint.2012.08.1255>
- 1507 Reitner, J.M., 2007. Glacial dynamics at the beginning of Termination I in the Eastern Alps
1508 and their stratigraphic implications. *Quat. Int.* 164, 64–84.
1509 <https://doi.org/10.1016/j.quaint.2006.12.016>
- 1510 Reuther, A.U., Urdea, P., Geiger, C., Ivy-Ochs, S., Niller, H.-P., Kubik, P.W., Heine, K.,
1511 2007. Late Pleistocene glacial chronology of the Pietrele Valley, Retezat Mountains,
1512 Southern Carpathians constrained by ¹⁰Be exposure ages and pedological
1513 investigations. *Quat. Int.* 164, 151–169. <https://doi.org/10.1016/j.quaint.2006.10.011>
- 1514 Revel, M., Ducassou, E., Grousset, F.E., Bernasconi, S.M., Migeon, S., Révillon, S., Mascle,
1515 J., Murat, A., Zaragosi, S., Bosch, D., 2010. 100,000 years of African monsoon
1516 variability recorded in sediments of the Nile margin. *Quat. Sci. Rev.* 29, 1342–1362.
1517 <https://doi.org/10.1016/j.quascirev.2010.02.006>
- 1518 Riboulot, V., Cattaneo, A., Scalabrin, C., Gaillot, A., Jouet, G., Ballas, G., Marsset, T.,
1519 Garziglia, S., Ker, S., 2017. Control of the geomorphology and gas hydrate extent on
1520 widespread gas emissions offshore Romania. *Bulletin De La Societe Geologique De*
1521 *France* 188 (4), 26. <https://doi.org/10.1051/bsgf/2017182>
- 1522 Ross, D.A., Degens, E.T., MacIlvaine, J., 1970. Black Sea: recent sedimentary history.
1523 *Science* 170, 163–165. <https://doi.org/10.1126/science.170.3954.163>
- 1524 Ross, D.A., Degens, E.T., 1974. Recent sediments of Black Sea. In: Degens, E.T., Ross, D.A.
1525 (Eds.), *The Black Sea: Geology, Chemistry, and Biology*. American Association of
1526 Petroleum Geologists, Tulsa, 183–199.
- 1527 Rossato, S., Mozzi, P., 2016. Inferring LGM sedimentary and climatic changes in the
1528 southern Eastern Alps foreland through the analysis of a ¹⁴C ages database (Brenta
1529 megafan, Italy). *Quat. Sci. Rev.* 148, 115–127.
1530 <https://doi.org/10.1016/j.quascirev.2016.07.013>
- 1531 Ryan, W.B., Major, C.O., Lericolais, G., Goldstein, S.L., 2003. Catastrophic flooding of the
1532 Black Sea. *Annual Rev. Earth. Planet. Sci.* 31, 525–554.
1533 <https://doi.org/10.1146/annurev.earth.31.100901.141249>
- 1534 Ryan, W.B., Pitman III, W.C., Major, C.O., Shimkus, K., Moskalenko, V., Jones, G.A.,
1535 Dimitrov, P., Gorür, N., Sakingç, M., Yüce, H., 1997. An abrupt drowning of the Black
1536 Sea shelf. *Mar. Geol.* 138, 119–126. [https://doi.org/10.1016/S0025-3227\(97\)00007-8](https://doi.org/10.1016/S0025-3227(97)00007-8)
- 1537 Sanchez Goñi, M.F., Harrison, S.P., 2010. Millennial-scale climate variability and vegetation
1538 changes during the Last Glacial: Concepts and terminology. *Quat. Sci. Rev.* 29, 2823–
1539 2827. <https://doi.org/10.1016/j.quascirev.2009.11.014>
- 1540 Schenk, F., Väiliranta, M., Muschitiello, F., Tarasov, L., Heikkilä, M., Björck, S., Brandefelt,
1541 J., Johansson, A.V., Näslund, J.-O., Wohlfarth, B., 2018. Warm summers during the
1542 Younger Dryas cold reversal. *Nature Com.* 9. [https://doi.org/10.1038/s41467-018-](https://doi.org/10.1038/s41467-018-04071-5)
1543 [04071-5](https://doi.org/10.1038/s41467-018-04071-5)

- 1544 Sanchi, L., Ménot, G., Bard, E., 2014. Insights into continental temperatures in the
1545 northwestern Black Sea area during the Last Glacial period using branched tetraether
1546 lipids. *Quat. Sci. Rev.*, 84, 98-108. <https://doi.org/10.1016/j.quascirev.2013.11.013>
- 1547 Schmieder, K., Schünemann, B., Schröder, H.G., 2004. Spatial patterns of surface sediment
1548 variables in the littoral zone of Lake Constance (Germany). *Archiv für Hydrobiologie*
1549 161, 455–468. <https://doi.org/10.1127/0003-9136/2004/0161-0455>
- 1550 Schramm, J.-M., 1991. The Permian–Triassic of the Gartnerkofel-1 Core (Carnic Alps,
1551 Austria): Illite crystallinity in shaly sediments and its comparison with pre-Variscan
1552 sequences. *Abh Geol BA* 45, 69–77.
- 1553 Schumilovskikh, L. S., Fleitmann, D., Nowaczyk, N. R., Behling, H., Marret, F., Wegwerth,
1554 A., Arz, H. W., 2014. Orbital and millennial-scale environmental changes between 64
1555 and 25 ka BP recorded in Black Sea sediments. *Clim. Past*, 10, 939-945.
1556 <https://doi.org/10.5194/cp-10-939-2014>
- 1557 Seguinot, J., Jouvet, G., Huss, M., Funk, M., Ivy-Ochs, S., Preusser, F., 2018. Modelling last
1558 glacial cycle ice dynamics in the Alps. *The Cryosphere Discussions* 1–30.
1559 <https://doi.org/10.5194/tc-2018-8>
- 1560 Sidorchuk, A.Y., Panin, A.V., Borisova, O.K., 2011. Surface runoff to the Black Sea from the
1561 East European Plain during Last Glacial Maximum–Late Glacial time. *Spec Pap Geol*
1562 *Soc Am* 473, 1–25.
- 1563 Sidorchuk, A.Y., Panin, A.V., Borisova, O.K., 2008. Climate-induced changes in surface
1564 runoff on the North-Eurasian plains during the late glacial and Holocene. *Water*
1565 *Resources* 35, 386–396. <https://doi.org/10.1134/S0097807808040027>
- 1566 Simpson, G., Castellort, S., 2012. Model shows that rivers transmit high-frequency climate
1567 cycles to the sedimentary record. *Geology* 40, 1131–1134.
1568 <https://doi.org/10.1130/G33451.1>
- 1569 Sionneau, T., Bout-Roumazeilles, V., Biscaye, P.E., Van Vliet-Lanoe, B., Bory, A., 2008.
1570 Clay mineral distributions in and around the Mississippi River watershed and Northern
1571 Gulf of Mexico: sources and transport patterns. *Quat. Sci. Rev.* 27, 1740–1751.
1572 <https://doi.org/10.1016/j.quascirev.2008.07.001>
- 1573 Skinner, L. C., Fallon, S., Waelbroeck, C., Michel, E., & Barker, S., 2010. Ventilation of the
1574 deep Southern Ocean and deglacial CO₂ rise. *Science*, 328 (5982), 1147-1151.
1575 <https://doi.org/10.1126/science.1183627>
- 1576 Smalley, I.J., Leach, J.A., 1978. The origin and distribution of the loess in the Danube Basin
1577 and associated regions of east-central Europe: a review. *Sed. Geol.* 21, 1–26.
1578 [https://doi.org/10.1016/0037-0738\(78\)90031-3](https://doi.org/10.1016/0037-0738(78)90031-3)
- 1579 Sommerwerk, N., Hein, T., Schneider-Jajoby, M., Baumgartner, C., Ostojic, M., Paunovic,
1580 M., Bloesch, J., Siber, R., Tockner, K., 2009. The Danube River Basin. In: K. Tockner,
1581 C.T. Robinson, U. Uehlinger (Eds.), *Rivers of Europe*, Elsevier Ltd., London, UK
1582 (2009), 59-113
- 1583 Soulet, G., Delaygue, G., Vallet-Coulomb, C., Böttcher, M.E., Sonzogni, C., Lericolais, G.,
1584 Bard, E., 2010. Glacial hydrologic conditions in the Black Sea reconstructed using
1585 geochemical pore water profiles. *Earth. Planet. Sci. Lett.* 296, 57–66.
1586 <https://doi.org/10.1016/j.epsl.2010.04.045>

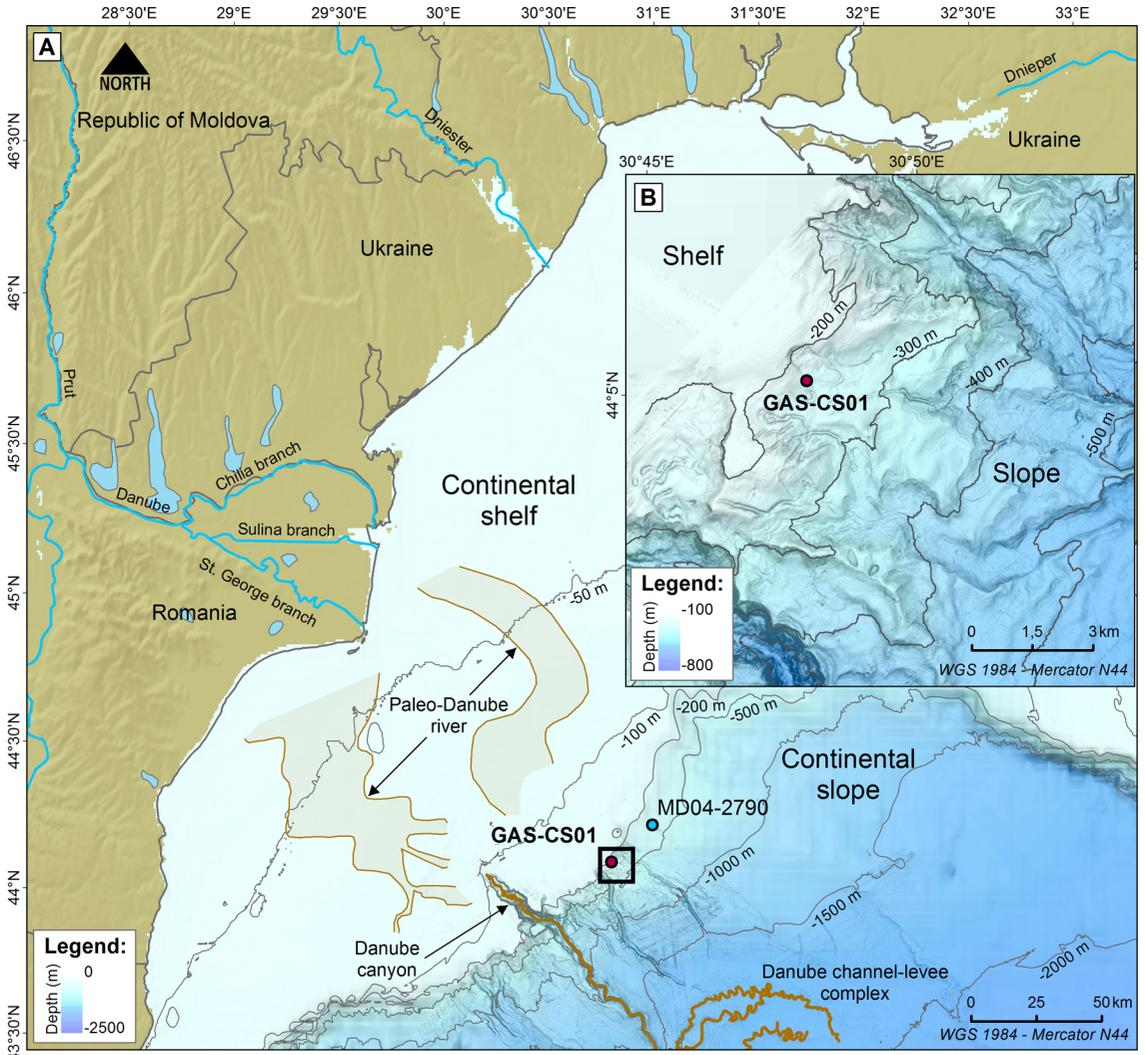
- 1587 Soulet, G., Giosan, L., Flux, C., Galy, V., 2019. Using Stable Carbon Isotopes to Quantify
1588 Radiocarbon Reservoir Age Offsets in the Coastal Black Sea. *Radiocarbon* 61, 309–
1589 318. <https://doi.org/10.1017/RDC.2018.61>
- 1590 Soulet, G., Ménot, G., Garreta, V., Rostek, F., Zaragosi, S., Lericolais, G., Bard, E. 2011a.
1591 Black Sea “Lake” reservoir age evolution since the Last Glacial-hydrologic and
1592 climatic implications. *Earth Planet. Sci.Lett.*, 308(1-2), 245-258.
1593 <https://doi.org/10.1016/j.epsl.2011.06.002>
- 1594 Soulet, G., Ménot, G., Lericolais, G., Bard, E., 2011b. A revised calendar age for the last
1595 reconnection of the Black Sea to the global ocean. *Quat. Sci. Rev.* 30, 1019–1026.
1596 <https://doi.org/10.1016/j.quascirev.2011.03.001>
- 1597 Soulet, G., Ménot, G., Bayon, G., Rostek, F., Ponzevera, E., Toucanne, S., Lericolais, G.,
1598 Bard, E., 2013. Abrupt drainage cycles of the Fennoscandian Ice Sheet. *Proc. Natl.*
1599 *Acad. Sci. USA* 110, 6682–6687. <https://doi.org/10.1073/pnas.1214676110>
- 1600 Spötl, C., Reimer, P.J., Starnberger, R., Reimer, R.W., 2013. A new radiocarbon chronology
1601 of Baumkirchen, stratotype for the onset of the Upper Würmian in the Alps: a new
1602 radiocarbon chronology of baumkirchen. *J. Quat. Sci.* 28, 552–558.
1603 <https://doi.org/10.1002/jqs.2645>
- 1604 Starkel, L., Michczyńska, D.J., Gębica, P., Kiss, T., Panin, A., Perşoiu, I., 2015. Climatic
1605 fluctuations reflected in the evolution of fluvial systems of Central-Eastern Europe
1606 (60–8 ka cal BP). *Quat. Int.* 388, 97–118. <https://doi.org/10.1016/j.quaint.2015.04.017>
- 1607 Starnberger, R., Drescher-Schneider, R., Reitner, J.M., Rodnight, H., Reimer, P.J., Spötl, C.,
1608 2013. Late Pleistocene climate change and landscape dynamics in the Eastern Alps:
1609 the inner-alpine Unterangerberg record (Austria). *Quat. Sci. Rev.* 68, 17–42.
1610 <https://doi.org/10.1016/j.quascirev.2013.02.008>
- 1611 Starnberger, R., Rodnight, H., Spötl, C., 2011. Chronology of the last glacial maximum in the
1612 Salzach Palaeoglacier area (Eastern Alps). *J. Quat. Sci.* 26, 502–510.
1613 <https://doi.org/10.1002/jqs.1477>
- 1614 Starnberger, R., Terhorst, B., Rähle, W., Peticzka, R., Haas, J.N., 2009. Palaeoecology of
1615 Quaternary periglacial environments during OIS-2 in the forefields of the Salzach
1616 Glacier (Upper Austria). *Quat. Int.* 198, 51–61.
1617 <https://doi.org/10.1016/j.quaint.2008.06.011>
- 1618 Stoffers, P., Müller, G., 1978. Mineralogy and lithofacies of Black Sea sediments, Leg 42B
1619 deep sea drilling project. Initial Reports of the Deep Sea Drilling Project 42, 373–411.
- 1620 Stroeven, A.P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow,
1621 B.W., Harbor, J.M., Jansen, J.D., Olsen, L., 2016. Deglaciation of fennoscandia. *Quat.*
1622 *Sci. Rev.* 147, 91–121. <https://doi.org/10.1016/j.quascirev.2015.09.016>
- 1623 Swierczynski, T., Lauterbach, S., Dulski, P., Delgado, J., Merz, B., Brauer, A., 2013. Mid-to
1624 late Holocene flood frequency changes in the northeastern Alps as recorded in varved
1625 sediments of Lake Mondsee (Upper Austria). *Quat. Sci. Rev.* 80, 78–90.
1626 <https://doi.org/10.1016/j.quascirev.2013.08.018>
- 1627 Tanaka, T., Togashi, S., Kamioka, H., Amakawa, H., Kagami, H., Hamamoto, T., Yuhara, M.,
1628 Orihashi, Y., Yoneda, S., Shimizu, H., 2000. JNdi-1: a neodymium isotopic reference
1629 in consistency with LaJolla neodymium. *Chem. Geol.* 168, 279–281.
1630 [https://doi.org/10.1016/S0009-2541\(00\)00198-4](https://doi.org/10.1016/S0009-2541(00)00198-4)

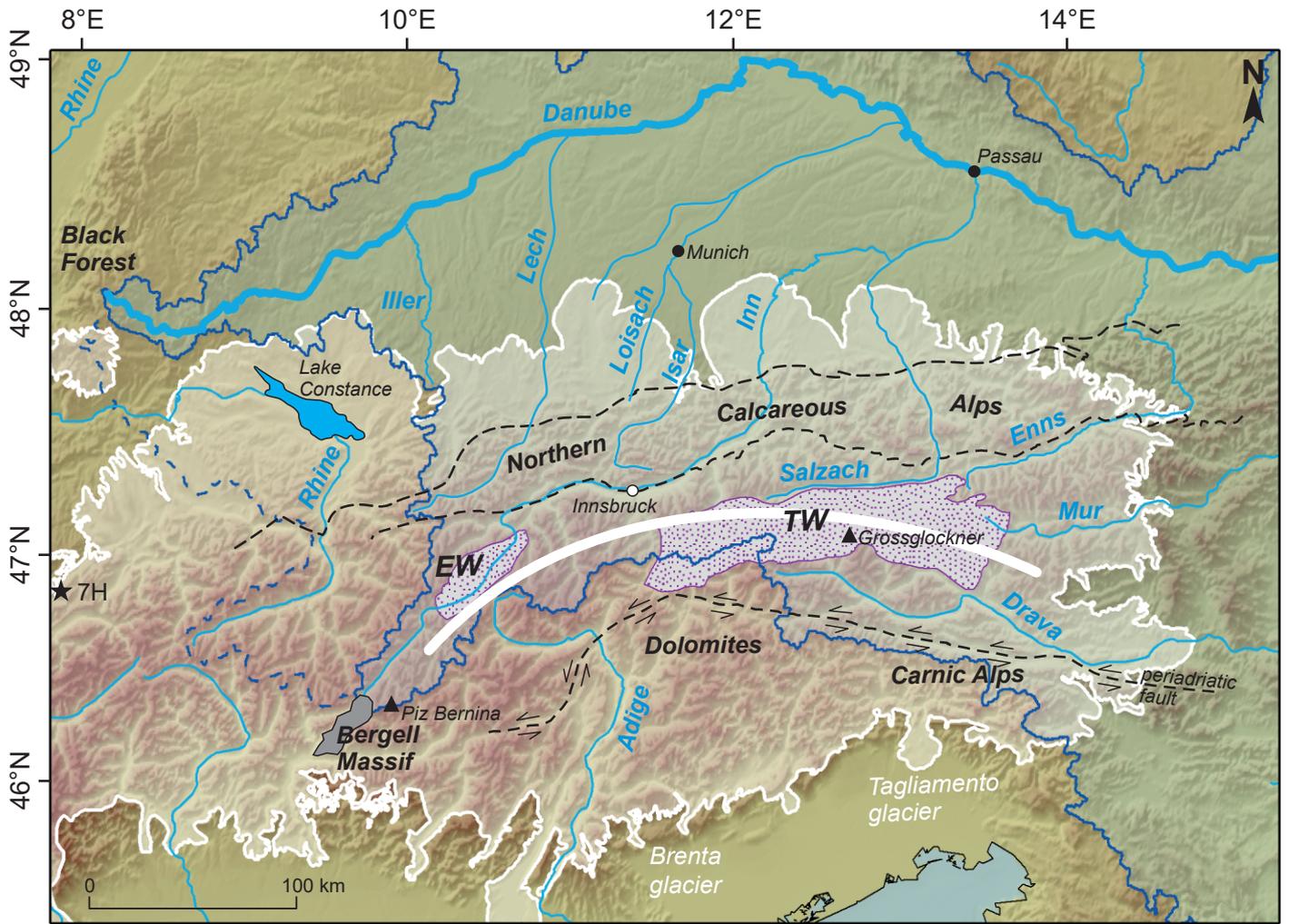
- 1631 Toucanne, S., Soulet, G., Freslon, N., Jacinto, R.S., Dennielou, B., Zaragosi, S., Eynaud, F.,
1632 Bourillet, J.-F., Bayon, G., 2015. Millennial-scale fluctuations of the European Ice
1633 Sheet at the end of the last glacial, and their potential impact on global climate. *Quat.*
1634 *Sci. Rev.* 123, 113–133. <https://doi.org/10.1016/j.quascirev.2015.06.010>
- 1635 Toucanne, S., Zaragosi, S., Bourillet, J.F., Cremer, M., Eynaud, F., Van Vliet-Lanoë, B.,
1636 Pénaud, A., Fontanier, C., Turon, J.L., Cortijo, E., 2009. Timing of massive ‘Fleuve
1637 Manche’ discharges over the last 350 kyr: insights into the European ice-sheet
1638 oscillations and the European drainage network from MIS 10 to 2. *Quat. Sci. Rev.* 28,
1639 1238–1256. <https://doi.org/10.1016/j.quascirev.2009.01.006>
- 1640 Toucanne, S., Zaragosi, S., Bourillet, J.-F., Marieu, V., Cremer, M., Kageyama, M., Van
1641 Vliet-Lanoë, B., Eynaud, F., Turon, J.-L., Gibbard, P.L., 2010. The first estimation of
1642 Fleuve Manche palaeoriver discharge during the last deglaciation: Evidence for
1643 Fennoscandian ice sheet meltwater flow in the English Channel ca 20–18 ka ago.
1644 *Earth Planet. Sci. Lett.* 290, 459–473. <https://doi.org/10.1016/j.epsl.2009.12.050>
- 1645 Tudryn, A., Leroy, S.A., Toucanne, S., Gibert-Brunet, E., Tucholka, P., Lavrushin, Y.A.,
1646 Dufaure, O., Miska, S., Bayon, G., 2016. The Ponto-Caspian basin as a final trap for
1647 southeastern Scandinavian Ice-Sheet meltwater. *Quat. Sci. Rev.* 148, 29–43.
1648 <https://doi.org/10.1016/j.quascirev.2016.06.019>
- 1649 Újvári, G., Kovács, J., Varga, G., Raucsik, B., Marković, S.B., 2010. Dust flux estimates for
1650 the Last Glacial Period in East Central Europe based on terrestrial records of loess
1651 deposits: a review. *Quat. sci. Rev.* 29, 3157–3166.
1652 <https://doi.org/10.1016/j.quascirev.2010.07.005>
- 1653 Újvári, G., Varga, A., Ramos, F.C., Kovács, J., Németh, T., Stevens, T., 2012. Evaluating the
1654 use of clay mineralogy, Sr–Nd isotopes and zircon U–Pb ages in tracking dust
1655 provenance: An example from loess of the Carpathian Basin. *Chem. Geol.* 304, 83–96.
1656 <https://doi.org/10.1016/j.chemgeo.2012.02.007>
- 1657 Urdea, P., 2004. The Pleistocene glaciation of the Romanian Carpathians, in: *Developments*
1658 *in Quaternary Sciences*. Elsevier, pp. 301–308.
- 1659 Van Exem, A., Debret, M., Copard, Y., Verpoorter, C., De Wet, G., Lecoq, N., Sorrel, P.,
1660 Werner, A., Roof, S., Laignel, B., 2019. New source-to-sink approach in an arctic
1661 catchment based on hyperspectral core-logging (Lake Linné, Svalbard). *Quat. Sci.*
1662 *Rev.* 203, 128–140. <https://doi.org/10.1016/j.quascirev.2018.10.038>
- 1663 Van Husen, D., 2004. Quaternary glaciations in Austria, in: *Developments in Quaternary*
1664 *Sciences*. Elsevier, pp. 1–13.
- 1665 van Husen, D., 2000. Geological processes during the Quaternary. *Mitteilungen der*
1666 *Österreichischen Geologischen Gesellschaft* 92, 135–156.
- 1667 Vandenberghe, J., 2003. Climate forcing of fluvial system development: an evolution of ideas.
1668 *Quat. Sci. Rev.* 22, 2053–2060. [https://doi.org/10.1016/S0277-3791\(03\)00213-0](https://doi.org/10.1016/S0277-3791(03)00213-0)
- 1669 Vandenberghe, J., 2002. The relation between climate and river processes, landforms and
1670 deposits during the Quaternary. *Quat. Int.* 91, 17–23. [https://doi.org/10.1016/S1040-6182\(01\)00098-2](https://doi.org/10.1016/S1040-6182(01)00098-2)
1671
- 1672 Vidal, L., Menot, G., Joly, C., Bruneton, H., Rostek, F., Çağatay, M.N., Major, C., Bard, E.,
1673 2010. Hydrology in the Sea of Marmara during the last 23 ka: Implications for timing
1674 of Black Sea connections and sapropel deposition. *Paleoceanography* 25.
1675 <https://doi.org/10.1029/2009PA001735>

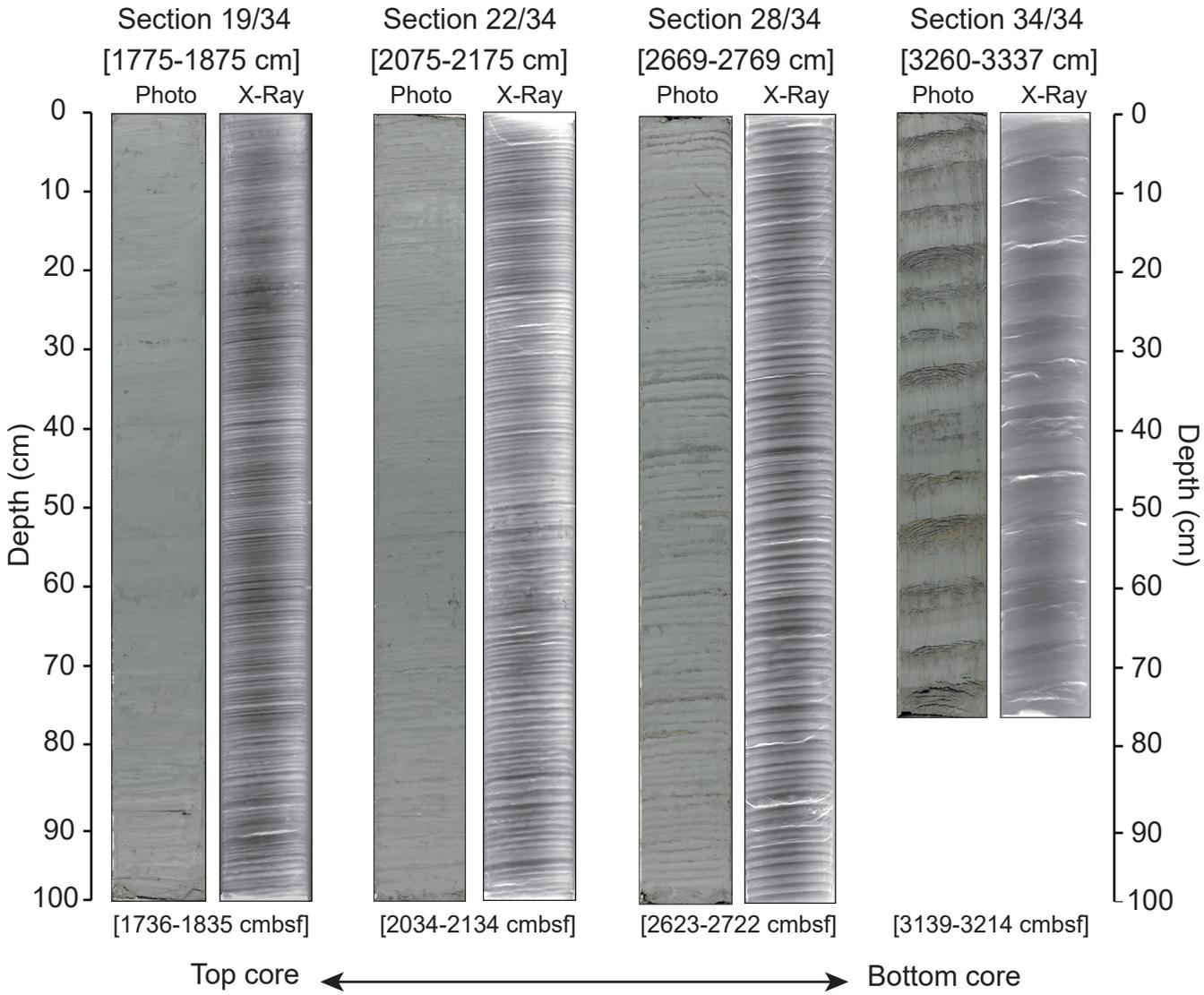
- 1676 Vishnevskaya, V.S., Sedaeva, K.M., 2000. Specific features of Early-Middle Carboniferous
1677 sedimentation in the southern part of the East European Platform. *Lithology and*
1678 *Mineral Resources* 35, 455–465.
- 1679 Wang, Y. J., Cheng, H., Edwards, R. L., An, Z. S., Wu, J. Y., Shen, C. C., Dorale, J. A., 2001.
1680 A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave,
1681 China. *Science*, 294 (5550), 2345-2348. <https://doi.org/10.1126/science.1064618>
- 1682 Wegwerth, A., Kaiser, J., Dellwig, O., Shumilovskikh, L. S., Nowaczyk, N. R., Arz, H. W.,
1683 2016. Northern hemisphere climate control on the environmental dynamics in the
1684 glacial Black Sea 'Lake'. *Quat. Sci.Rev.* 135, 41-53.
1685 <https://doi.org/10.1016/j.quascirev.2016.01.016>
- 1686 Wirsig, C., Zasadni, J., Ivy-Ochs, S., Christl, M., Kober, F., Schlüchter, C., 2016. A
1687 deglaciation model of the Oberhasli, Switzerland. *J. Quat. Sci.* 31, 46–59.
1688 <https://doi.org/10.1002/jqs.2831>
- 1689 Wirth, S.B., Glur, L., Gilli, A., Anselmetti, F.S., 2013. Holocene flood frequency across the
1690 Central Alps–solar forcing and evidence for variations in North Atlantic atmospheric
1691 circulation. *Quat. Sci. Rev.* 80, 112–128.
1692 <https://doi.org/10.1016/j.quascirev.2013.09.002>
- 1693 Wong, H., Panin, N., Dinu, C., Georgescu, P., Rahn, C., 1994. Morphology and post-
1694 Chaudian (Late Pleistocene) evolution of the submarine Danube fan complex. *Terra*
1695 *Nova* 6, 502–511. <https://doi.org/10.1111/j.1365-3121.1994.tb00894.x>
- 1696 Wu, H., Guiot, J., Brewer, S., Guo, Z., 2007. Climatic changes in Eurasia and Africa at the
1697 last glacial maximum and mid-Holocene: reconstruction from pollen data using
1698 inverse vegetation modelling. *Climate Dynamics* 29, 211–229.
1699 <https://doi.org/10.1007/s00382-007-0231-3>
- 1700 Yanchilina, A.G., Ryan, W.B.F., McManus, J.F., Dimitrov, P., Dimitrov, D., Slavova, K.,
1701 Filipova-Marinova, M., 2017. Compilation of geophysical, geochronological, and
1702 geochemical evidence indicates a rapid Mediterranean-derived submergence of the
1703 Black Sea's shelf and subsequent substantial salinification in the early Holocene. *Mar.*
1704 *Geol.* 383, 14–34. <https://doi.org/10.1016/j.margeo.2016.11.001>
- 1705 Zaragosi, S., Bourillet, J.-F., Eynaud, F., Toucanne, S., Denhard, B., Van Toer, A., Lanfumey,
1706 V., 2006. The impact of the last European deglaciation on the deep-sea turbidite
1707 systems of the Celtic-Armorican margin (Bay of Biscay). *Geo-Mar. Lett.* 26, 317–329.
1708 <https://doi.org/10.1007/s00367-006-0048-9>
- 1709 Zaragosi, S., Eynaud, F., Pujol, C., Auffret, G.A., Turon, J.-L., Garlan, T., 2001. Initiation of
1710 the European deglaciation as recorded in the northwestern Bay of Biscay slope
1711 environments (Meriadzek Terrace and Trevelyan Escarpment): a multi-proxy
1712 approach. *Earth. Planet. Sci. Lett.* 188, 493–507. [https://doi.org/10.1016/S0012-](https://doi.org/10.1016/S0012-821X(01)00332-6)
1713 [821X\(01\)00332-6](https://doi.org/10.1016/S0012-821X(01)00332-6)

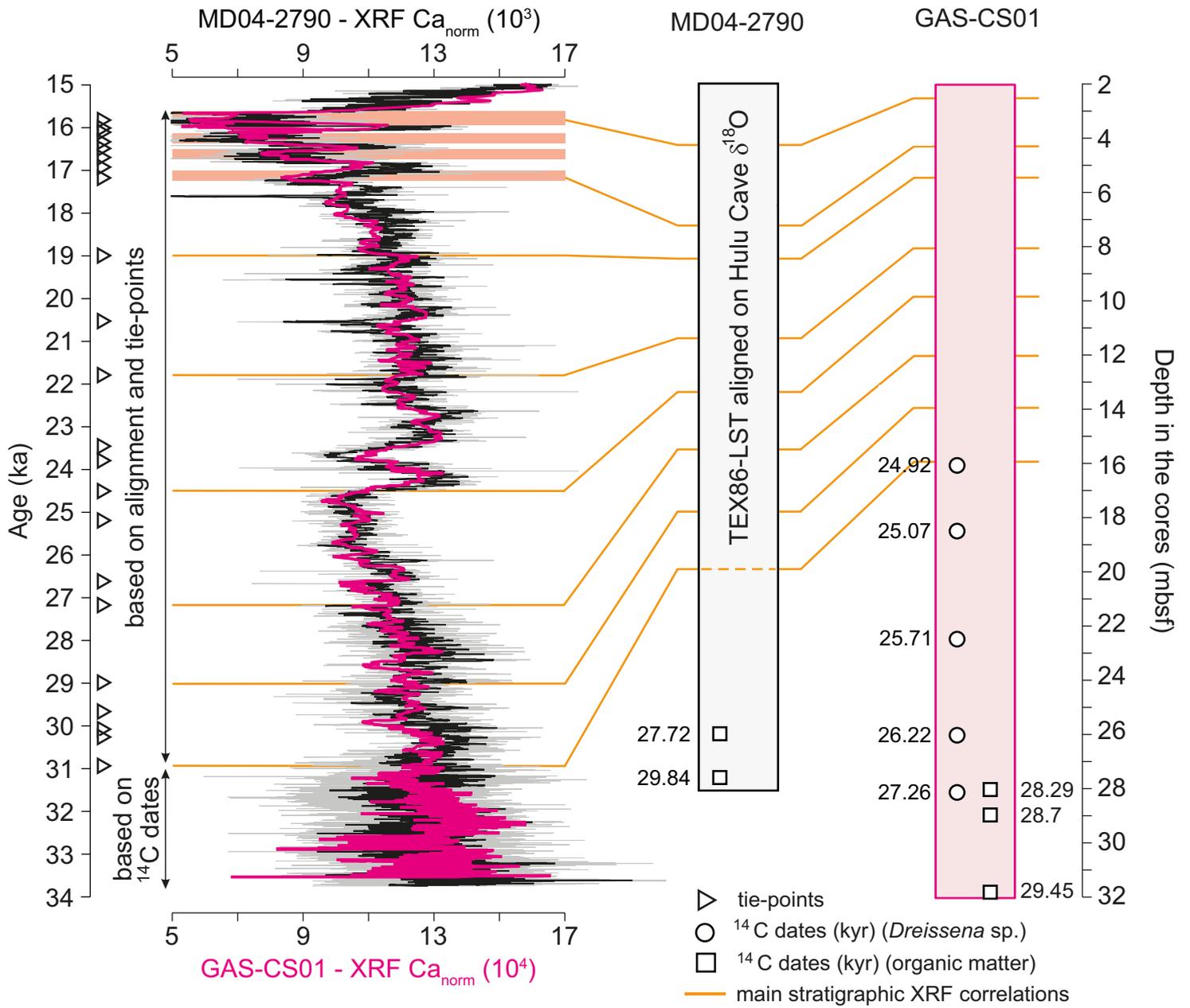
1714

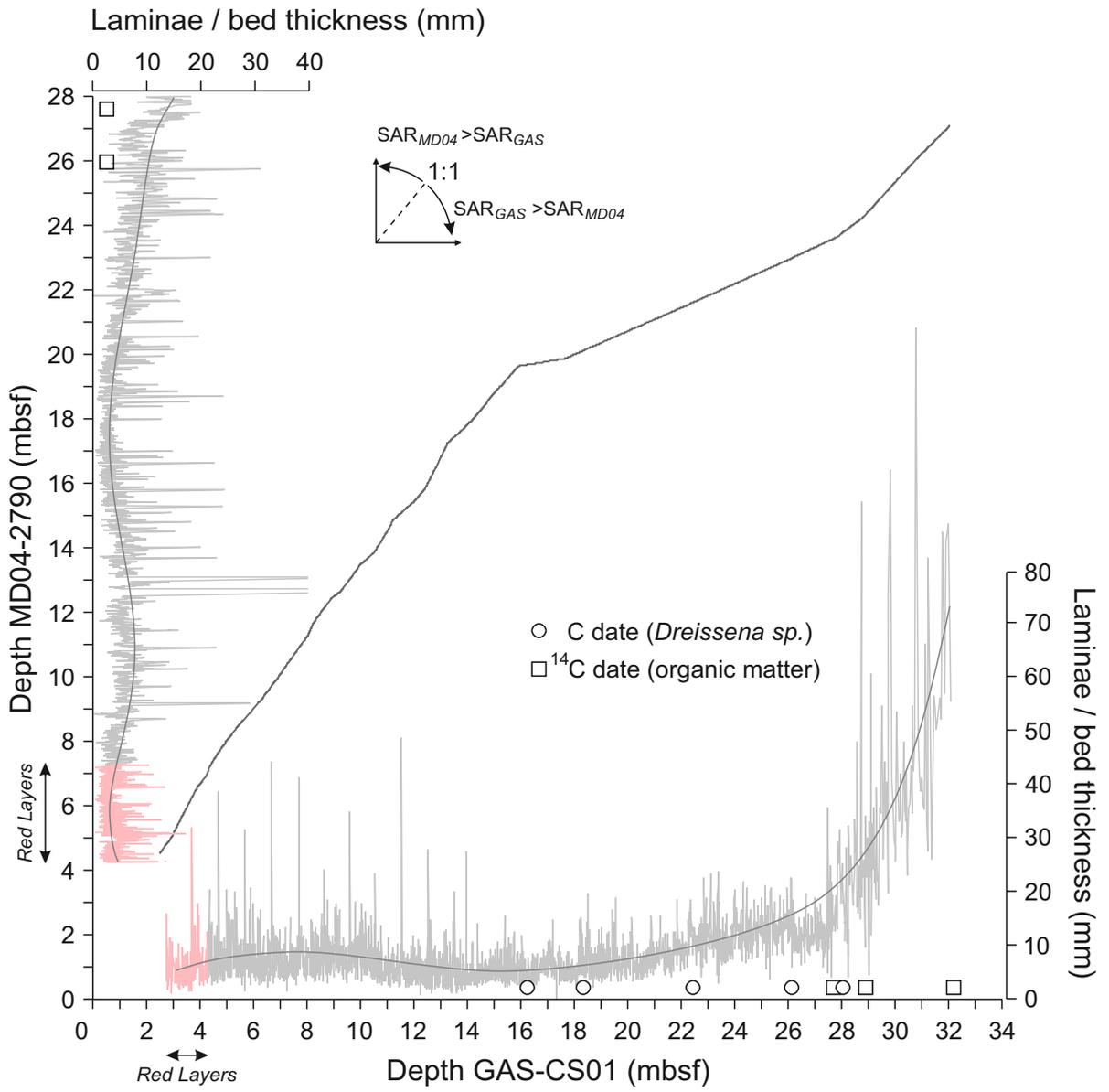


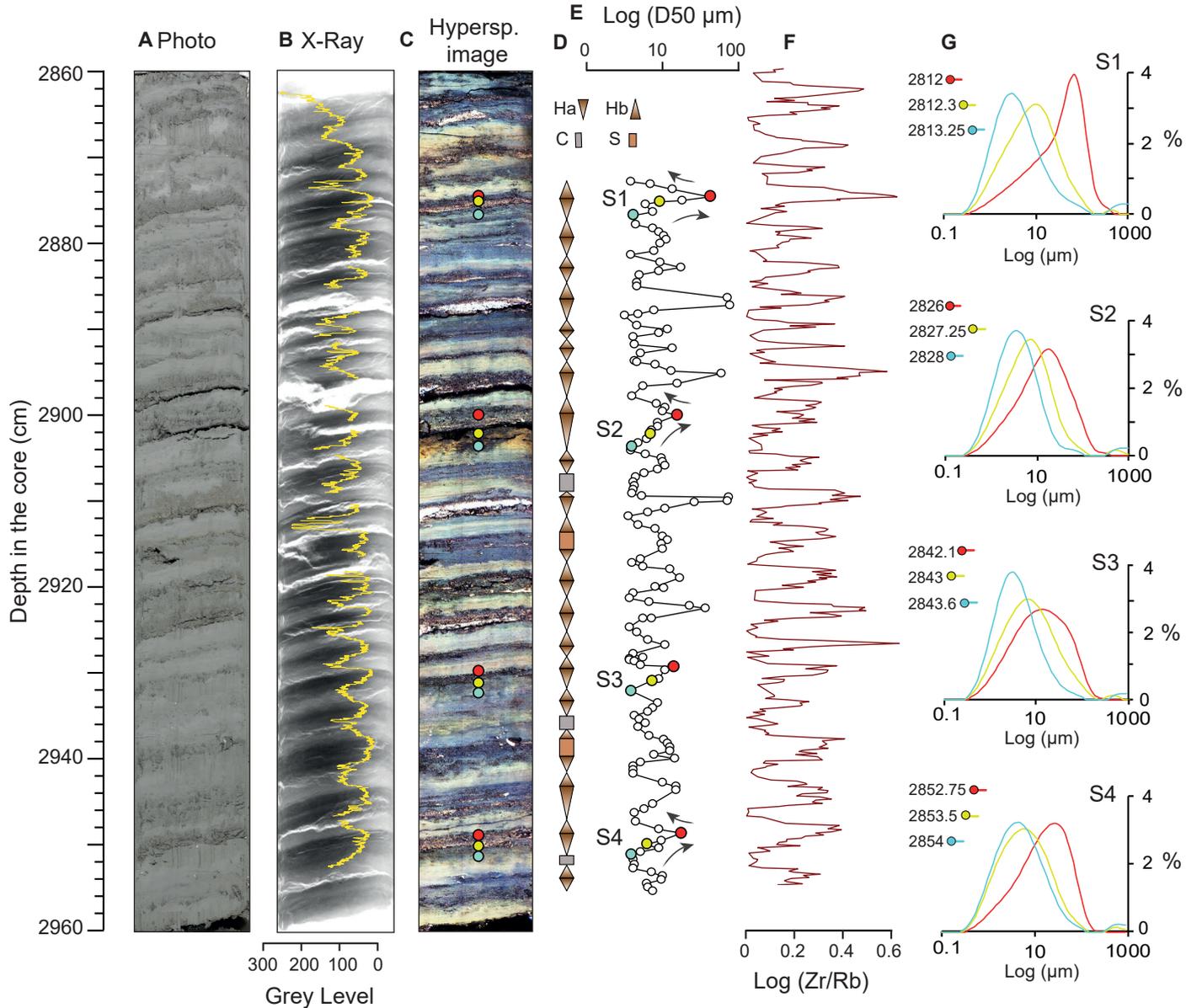


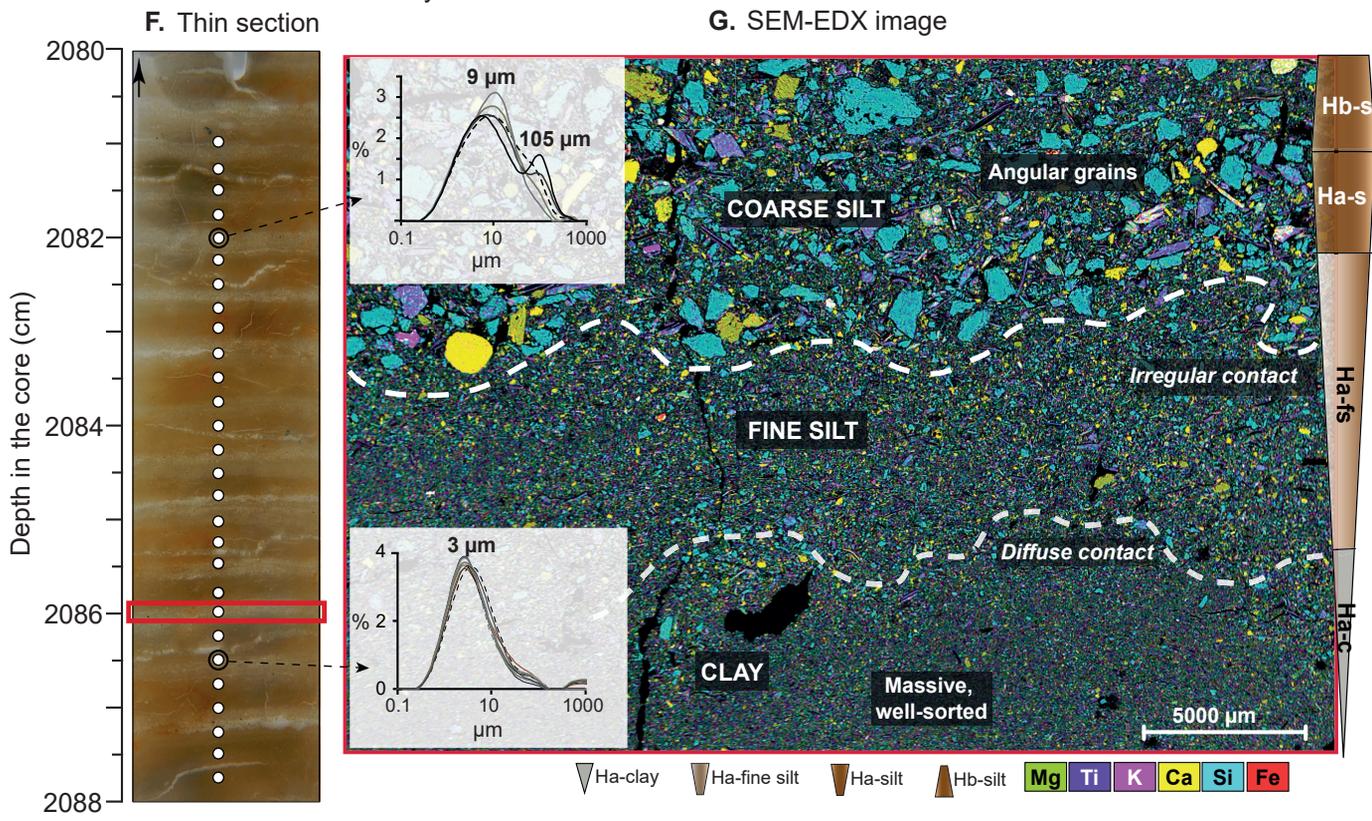
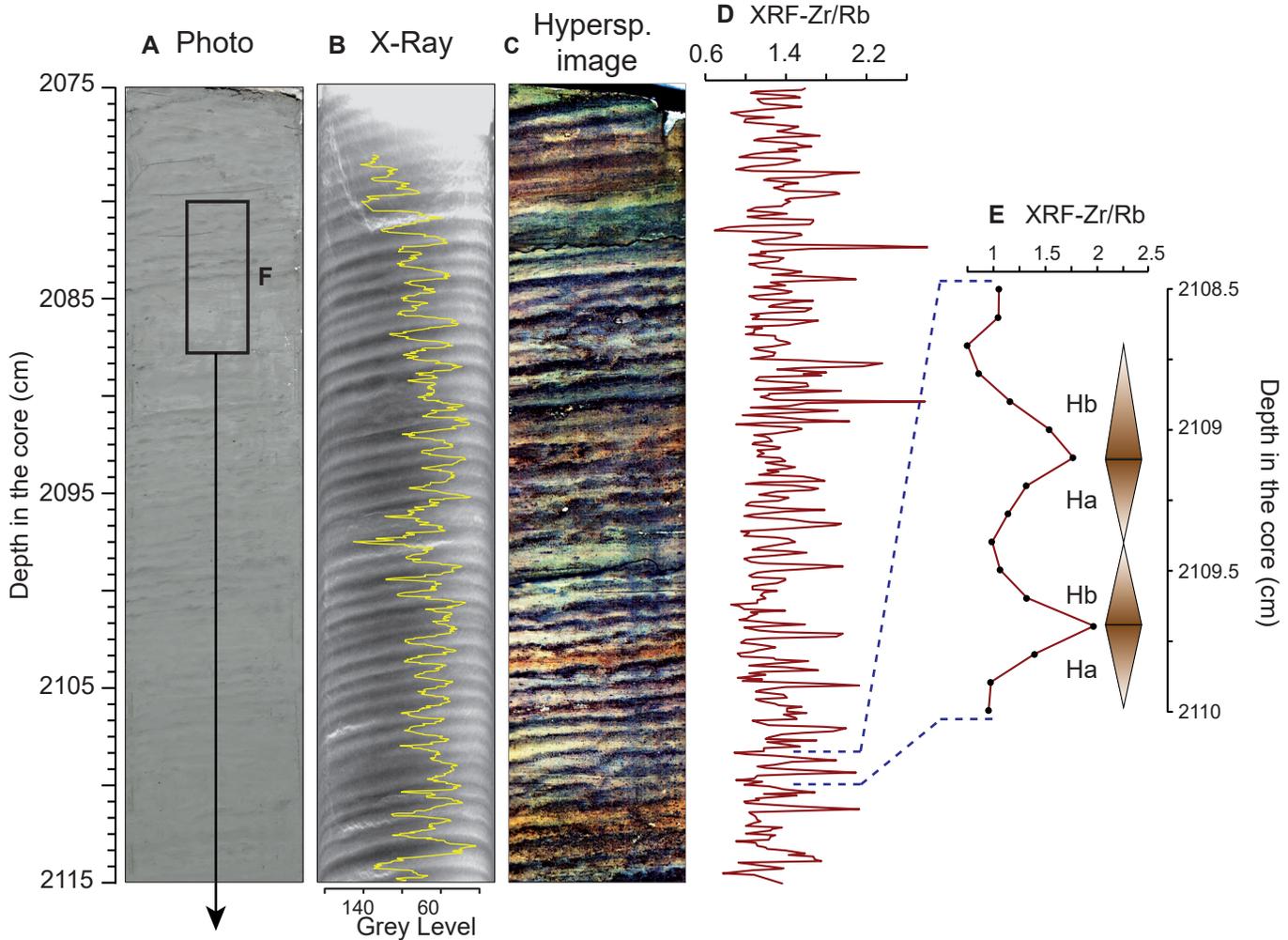


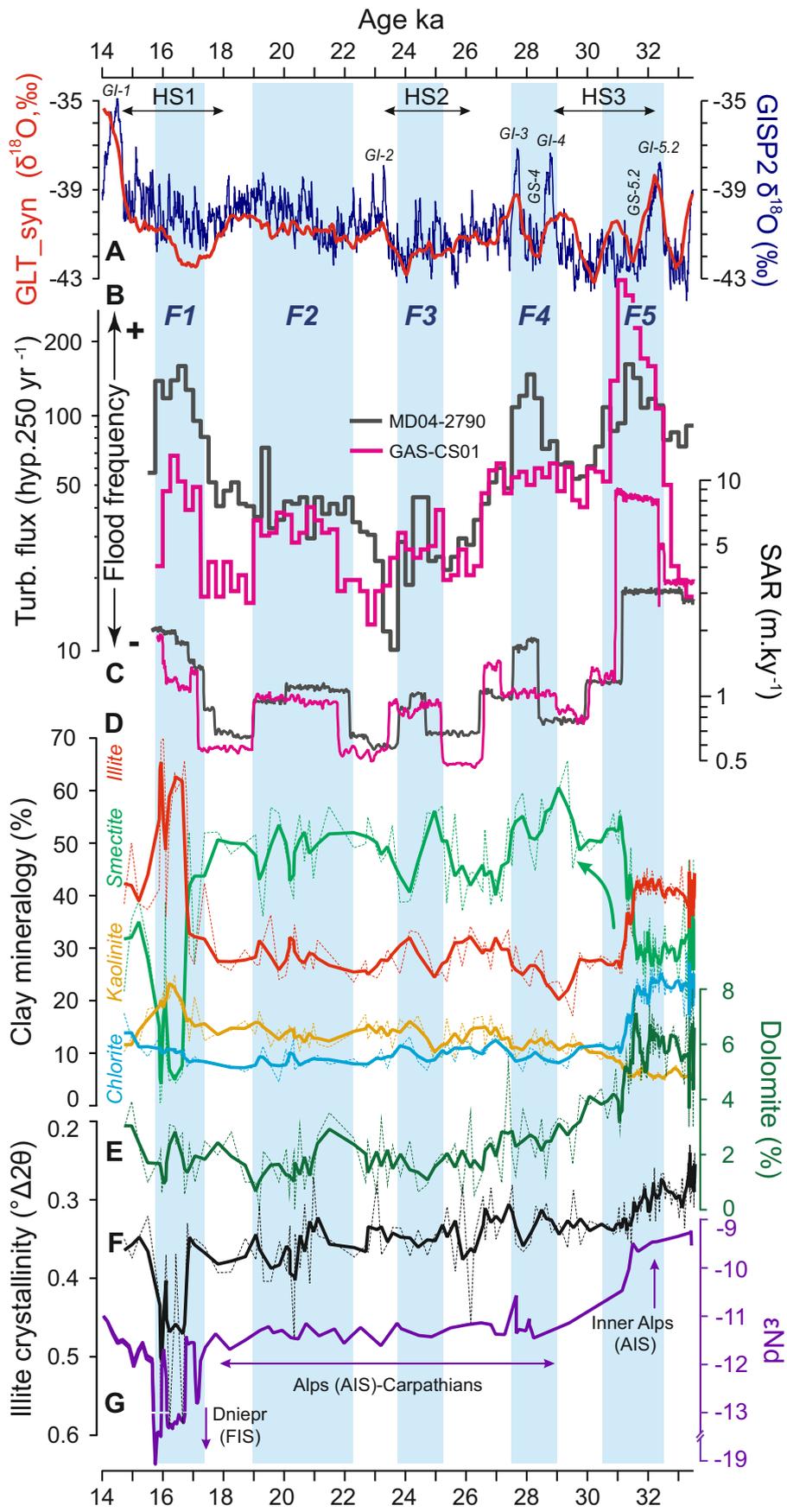


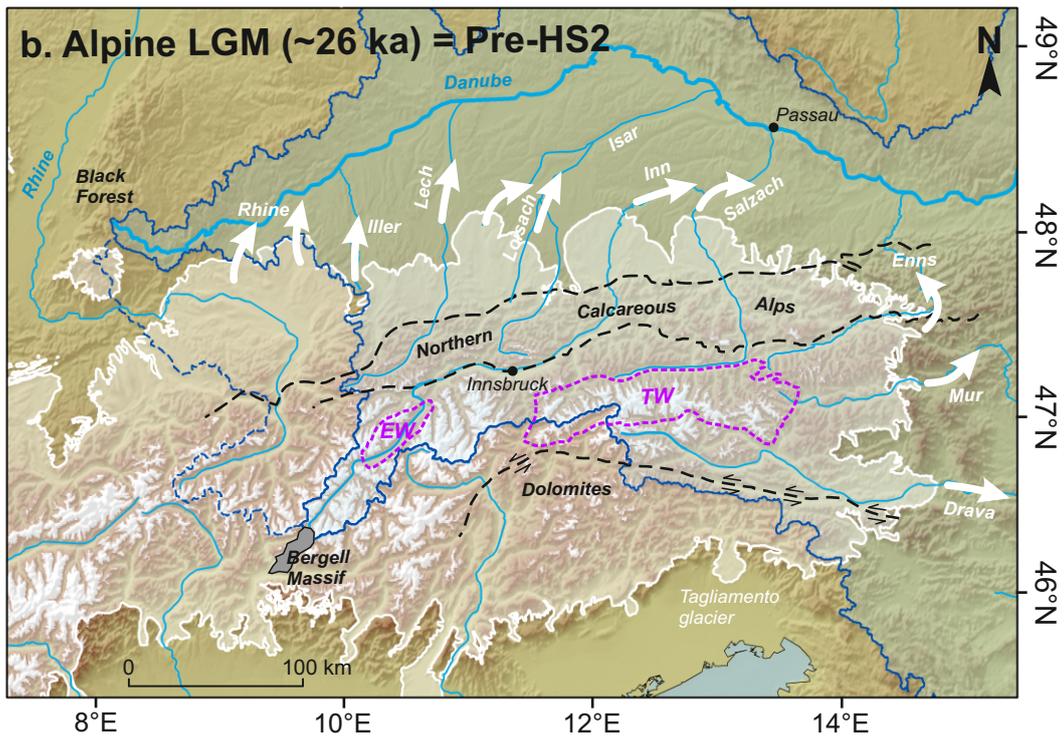
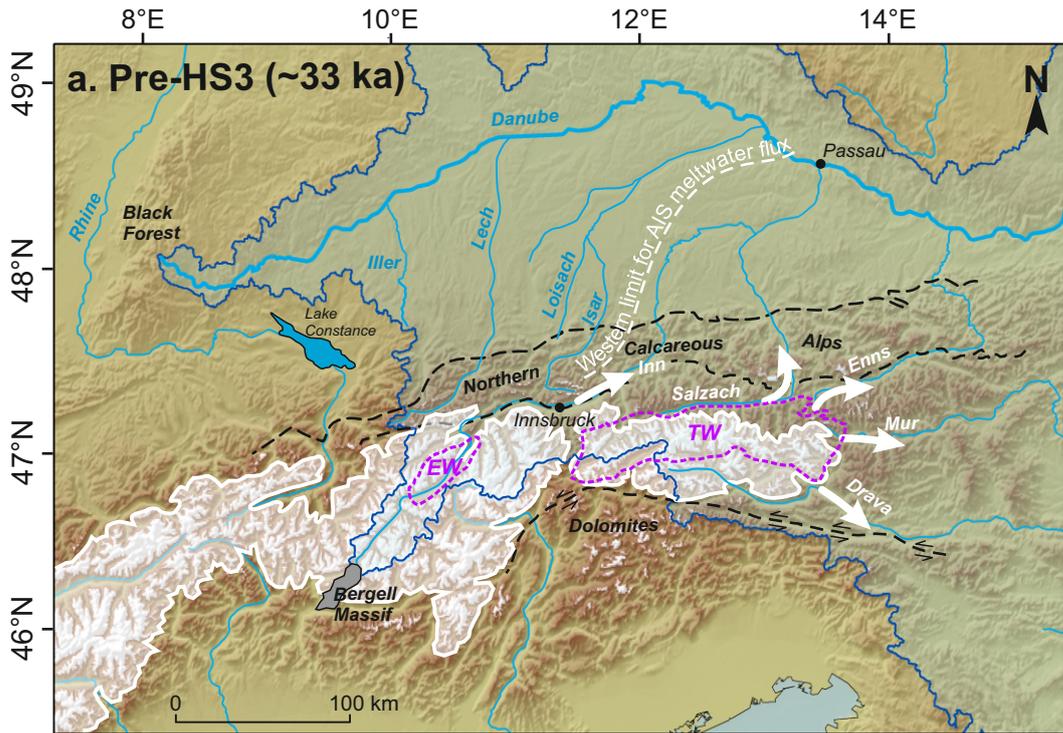


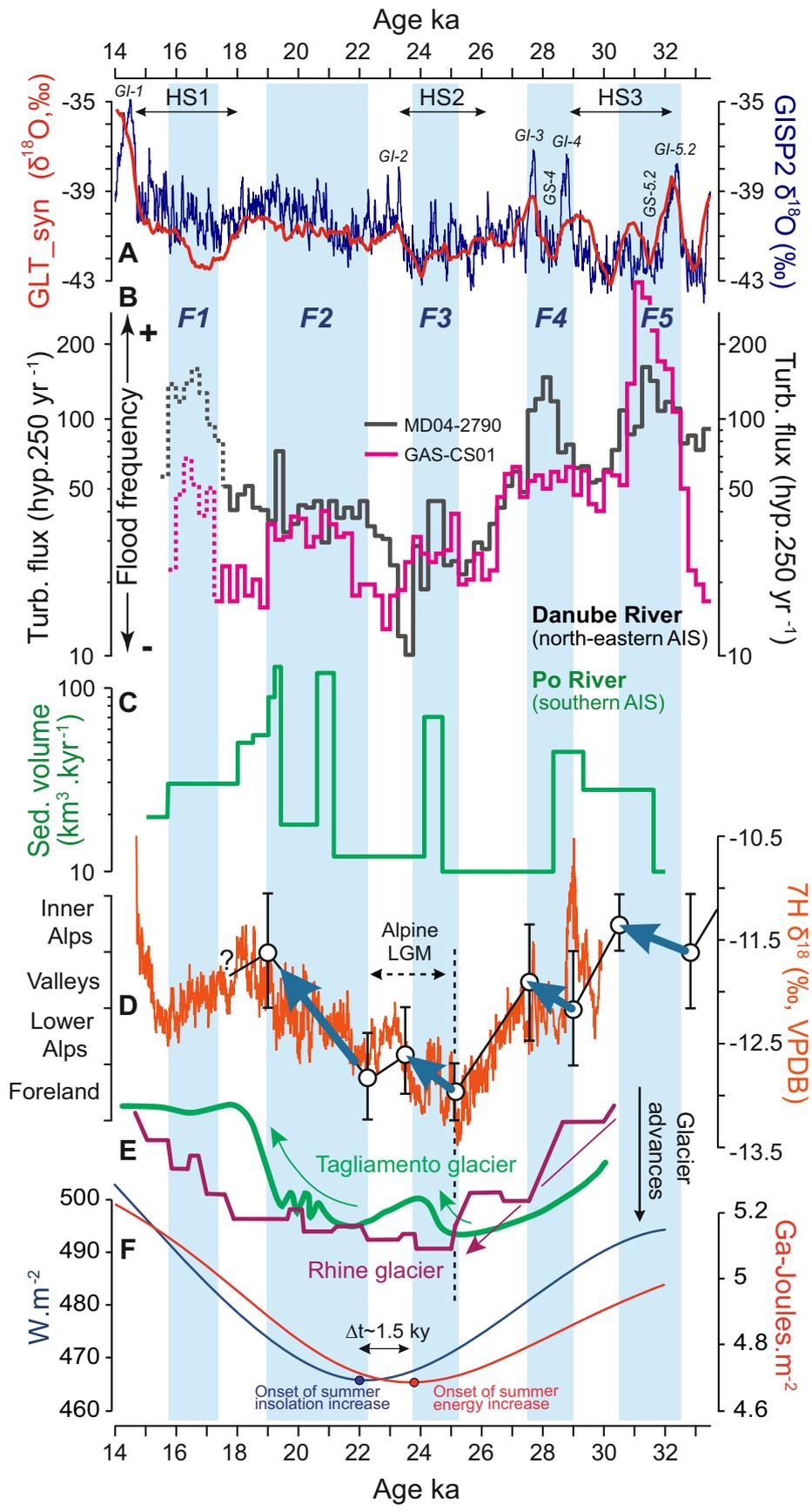












Core Label	Lat. N	Long. E	Water depth (m)	Length (m)	Year	Cruise	IGSN
GAS-CS01	44,0865	30,7993	240	33,4	2015	GHASS	http://igsn.org/BFBGX-127384
MD04-2790	44,2219	30,9935	362	30,3	2004	ASSEMBLAGE-1	http://igsn.org/BFBGX-88381

Core ID	Depth (cm) ^a	Depth (cmbsf) ^b	Lab. Number	Sample type	¹⁴ C age (yr BP)	error (1σ)
<u>GAS-CS01</u>						
GAS-CS01	1651	1614	Beta-440157	<i>Dreissena</i> sp.	24,920	120
GAS-CS01	1870	1831	Beta-440158	<i>Dreissena</i> sp.	25,070	120
GAS-CS01	2280	2238	Beta-463971	<i>Dreissena</i> sp.	25,710	110
GAS-CS01	2650	2604	Beta-463972	<i>Dreissena</i> sp.	26,220	110
GAS-CS01	2851	2796	Beta-479030	Organic matter	28,290	120
GAS-CS01	2853	2798	Beta-440160	<i>Dreissena</i> sp.	27,260	110
GAS-CS01	2955	2882	Beta-463973	Organic matter	28,700	140
GAS-CS01	3336	3214	Beta-479031	Organic matter	29,450	140
<u>MD04-2790</u>						
MD04-2790	2835	2600	Beta-477223	Organic matter	27,720	130
MD04-2790	3001	2765	Beta-463974	Organic matter	29,840	150

^a Raw (*i.e.* uncorrected) depth in cores

^b Corrected depth in cores (*i.e.* after removal of gaps), in cm below sea floor (cmbsf)

River	Drainage area (km ²)	Lat. N	Long. E	ICr (°Δ2θ)	Smectite (%)	Illite 2M1 (%)	Kaolinite (%)	Chlorite (%)	Dolomite (%)	
Danube Tributaires (n=12)										
<i>Alps (n=5)</i>				†	0.26 ± 0.04	9.2 ± 15.4	51.2 ± 13.3	4.4 ± 1.9	28.4 ± 3.8	11.2 ± 4.9
				‡	0.28 ± 0.04	12.2 ± 16.2	44.7 ± 12.6	5.6 ± 2.2	27.8 ± 3.9	9.6 ± 5.8
Iller	26,130	48,36232	10,00110	0,34	40	34	5	21	17	
Inn	26,128	47,78181	12,12609	0,28	0	38	3	29	6	
Enns	6,185	48,21270	14,48660	0,23	3	65	3	30	17	
upper Drava	40,087	46,60046	13,89860	0,2	0	66	3	31	10	
lower Drava	40,087	45,69050	18,41658	0,26	3	53	8	31	6	
<i>Dinarides (n=2)</i>				†	0.3 ± 0.04	25.5 ± 14.5	44.5 ± 9.5	17 ± 0	14 ± 5	1 ± 1
				‡	0.28 ± 0.04	19.2 ± 15.8	48.7 ± 10.4	17 ± 0	16.2 ± 5.5	1.4 ± 1.1
Sava	95,793	44,72358	20,30960	0,26	11	54	17	19	2	
Velika-Morava	37,571	44,60580	21,08620	0,34	40	35	17	9	0	
<i>Carpathians (n=5)</i>				†	0.3 ± 0	44.2 ± 25.5	34.4 ± 15	11.8 ± 7.2	9.4 ± 4.5	0.8 ± 0.8
				‡	0.3 ± 0	55.6 ± 28	27.6 ± 16.4	8.6 ± 7.9	7.7 ± 4.8	0.3 ± 0.9
Morava	27,267	48,19118	16,97450	0,3	32	38	21	9	0	
Tisza	15,609	46,14687	20,06457	0,3	55	28	8	8	0	
Siret	46,289	45,39911	28,01163	0,3	66	22	5	7	1	
Prut	28,568	45,47172	28,19500	0,3	68	22	5	5	1	
Vah	1,966	47,91403	18,01211	0,3	0	62	20	18	2	
<i>Alps + Dinarides + Carpathians (351,593km²)</i>				‡	0.28 ± 0.01	29.6 ± 19.1	40.4 ± 9.2	10.9 ± 4.9	16.6 ± 8.3	3.3 ± 4.2
Danube River (n=6)										
				†	0.3 ± 0.05	29.8 ± 17.5	39.6 ± 7.8	11 ± 5.5	19.5 ± 7.1	5.2 ± 1
Passau	801,093	48,59673	13,38283	0,39	3	41	23	33	0	
Upstream Tisza	801,093	45,16503	20,10953	0,28	24	46	8	22	6	
Upstream Sava	801,093	44,92347	20,32111	0,33	41	35	9	16	6	
Downstream Sava	801,093	44,66575	20,78006	0,27	15	52	11	21	4	
Moldava-Noua	801,093	44,69287	21,66701	0,29	42	37	7	14	4	
Braila	801,093	45,32294	28,00246	0,25	54	27	8	11	6	