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Timing and mechanisms of sediment accumulation and pedogenesis: Insights from the Po Plain (northern Italy)

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Abstract

Paleosol stratigraphy in the Po Plain, reconstructed through sedimentological analysis and correlation of ca. 170 core data chronologically constrained by 376 radiocarbon dates, revealed strict relationships between pedogenetic and fluvial processes in alluvial and paralic environments. Vertically stacked, weakly developed paleosols within Upper Pleistocene and Holocene mud-prone strata testify to intermittent pedogenesis, periodically interrupted by overbank sedimentation. Individual paleosols are laterally traceable for tens of km and exhibit A-Bk-Bw, A-Bk or A-Bw profiles. Stratigraphically ordered ^{14}C calibrated ages from A horizons testify to slow aggradation during 4-6 thousand years-long exposure periods. Burial ages, with an error of few centuries, are provided by plant debris at the top of A horizons.

Millennial-scale climate oscillations and glacio-eustasy are the main drivers of the pedo-sedimentary evolution of the area during the last 50 kyr. Pleistocene (P) paleosols developed in well-drained floodplain environments, dissected by fluvial incision, during relatively warm periods. Overbank sedimentation and paleosol burial occurred during colder phases. High-sediment-supply during the Last Glacial Maximum hindered pedogenesis and led to the accumulation of 3-10 m-thick overbank strata. Widespread soil development (paleosol PH) occurred at the end of Last Glacial Maximum, following glaciers retreat and afforestation of drainage basins. At distal locations, paleosol PH was progressively buried under estuarine sediments during the Holocene phases of post-glacial sea-level rise. Beyond the area of marine influence, burial ages of paleosol PH change from a place to another without specific spatial trends and reflect upstream fluvial sedimentation dominated by avulsions and deposition of spatially restricted alluvial units. Holocene (H) paleosols show a poor correlation potential and laterally variable degree of maturity that reflect avulsive

49 sedimentation patterns and crevassing. Deforestation and land reclamation affected pedo-
50 sedimentary processes during the last 6 kyr.

51

52

53 **Keywords**

54 Paleosol stratigraphy, pedo-sedimentary evolution, radiocarbon dates, climate change, eustasy,
55 Late Quaternary

56

57

58 **1. INTRO**

59

60 In alluvial settings, the development and burial of soil horizons are intimately related to fluvial
61 activity (Kraus and Bown, 1993) and governed by a variety of factors. High sediment supply and
62 fluvial aggradation inhibit pedogenesis (Demko et al., 2004), whereas low sediment supply and
63 fluvial incision promote soil development in interfluvial areas (Blum and Törnqvist, 2000). Climate
64 influences the amount of sediment delivered to the basins, modulating the magnitude and type of
65 precipitations, the vegetation cover of drainage areas and the river's transport capacity
66 (Vandenberghe, 2003). Alluvial sedimentation can be locally hindered or enhanced by tectonic
67 movements (Holbrook and Schumm, 1999; Viseras et al., 2003; Benvenuti et al., 2008; Pati et al.,
68 2019), differential subsidence (Cohen et al., 2003) or by avulsions and other processes related to
69 the intrinsic dynamics of the fluvial apparatus (Kraus, 1999; Cleveland et al., 2007; Hajek and
70 Wolinsky, 2012). In coastal settings, fluvial dynamics are strongly influenced by sea-level oscillations
71 (Atchley et al., 2004; Blum et al., 2013). Incised valleys (and associated interfluvial paleosols) related

72 to glacio-eustasy are a widely recognized trait in the sedimentary record (Shanley and McCabe,
73 1994; Aitken and Flint, 1996; McCarthy and Plint, 1998; Plint et al., 2001; Gibling et al., 2011).

74 The causal relationships between paleosol formation and alluvial sedimentation have been
75 reconstructed in ancient alluvial successions, where the geometric relationships between paleosols
76 and associated fluvial sediment bodies are superbly exposed (Gibling and Bird, 1994; McCarthy and
77 Plint, 2003; Dubiel and Hasiotis, 2011; Soares et al., 2020). However, the role of distinct controlling
78 factors on paleosol development and burial can hardly be assessed (Wright and Marriott, 1993;
79 Atchley et al., 2004), because of the temporal resolution of pre-Quaternary dating methods,
80 insufficient to describe pedo-sedimentary processes which typically act at millennial time scales
81 (Rasbury et al., 1997; Hofmann et al., 2017). Furthermore, diagenesis may have substantially
82 modified soil properties after burial, hindering comparison with modern soils and the reconstruction
83 of the soil-forming environment (Trendell et al., 2012).

84 Improved techniques of subsurface investigation have recently prompted the study of buried
85 upper Quaternary alluvial successions (Choi, 2005; Tsatskin et al., 2015; Amorosi et al., 2017a,b). In
86 this relatively narrow time window, drainage areas, ecosystems and soil-forming environment did
87 not change significantly. Moreover, the high temporal resolution of Quaternary dating methods
88 permits to link unequivocally pedogenetic processes to a well-known climate and eustatic history.

89 Radiocarbon is probably the most reliable dating method for the last 50 kyr (Reimer et al., 2020).
90 However, numerous uncertainties remain in the interpretation of ^{14}C dates from paleosols. Organic
91 carbon is continuously incorporated in soils, and subjected to complex, and not totally understood,
92 biological and physical transformations (Larionova et al., 2017; Meingast et al., 2020). These
93 processes can act at different velocity and magnitude, depending on climate, morphology of the
94 exposed surface, parent material, and vegetation (Alexandrovskiy and Chichagova, 1998; Kleber,
95 2010).

This study is based on refined pedostratigraphic reconstructions and on a vast ^{14}C dataset which permitted to chronologically constrain the major architectural and facies changes. The primary aim of this research is to understand the causes and mechanisms of soil development and burial in an alluvial-deltaic setting and its relation to fluvial and coastal dynamics. To this purpose, we focused on Upper Pleistocene-Holocene paleosols and on their stratigraphic relationship with older, coeval and younger pedo-sedimentary units. Secondary objectives are to discuss: (i) the relative role of global and local controlling factors on soil development and burial; (ii) the potential use (and major limitations) of radiocarbon to assess the exposure age of paleosols.

2. GEOLOGICAL SETTING

2.1. Structural setting and basin-scale stratigraphy

The Po sedimentary basin is enclosed in a natural amphitheatre bordered by the Alps, to west and to the north, and by the Apennines, to the south. The eastward prolongation of the Po Plain is the Adriatic epicontinental sea (Fig. 1). The most external thrusts of the Southern Alps and of Apennines, showing opposite vergence, locally face each other beneath the Po Plain (Fantoni et al., 2004). South-Alpine buried thrusts are arranged in a single wide arc running from Milan to the Garda Lake (Vannoli et al., 2015). The Apennine front is composed of three tectonically active arcuate thrust systems: from west to east, the Monferrato, Emilia and Ferrara-Romagna Arcs (Ghielmi et al., 2013). Thrusts of the Emilia and Ferrara Arcs are sealed beneath a pile of sediments with extremely variable thicknesses (from a few hundred metres to ca. 8 km; Amadori et al., 2019). These lateral variations in thickness are controlled by lateral changes in subsidence rates (Campo et al., 2020),

120 ranging between zero and 2 mm/y (Bruno et al., 2020a). The northern margin of the Apennines,
121 which corresponds to an out-of-sequence system of N-NE verging thrusts (Maestrelli et al., 2018),
122 has been involved in a generalized uplift since the Early Pleistocene (Argnani et al., 2003).

123 The Po Basin fill shows an overall regressive trend from deep-marine to continental and coastal
124 units (Ghielmi et al., 2013). Widespread alluvial sedimentation started in the Po Plain around 870
125 kyr B.P. (Muttoni et al., 2003, 2011; Gunderson et al., 2014). The Po River, flowing in W-E direction,
126 divides the alluvial plain in two sectors (Fig. 1A). In the northern sector, Alpine tributaries flow
127 entrenched in Pleistocene sandy units (Ravazzi et al., 2012; Fontana et al., 2014; Bruno et al., 2018).
128 To the south, paleosol-bearing Pleistocene muds are sealed by a thick (up to 30 m) Holocene alluvial
129 and paralic succession (Amorosi et al., 2017a, b). Early Holocene estuarine deposits typically onlap
130 onto Upper Pleistocene alluvial strata, testifying to the progressive drowning of the alluvial plain
131 after 11.5 cal kyr B.P. (Bruno et al., 2017). Following stabilization of sea-level, the Middle-Late
132 Holocene records the progressive filling of the Po estuary and the successive delta progradation
133 (Amorosi et al., 2017b, 2019).

134

135 **2.2. Paleosols of the Po Basin**

136

137 Highly weathered rubified soils have been reported from the Po Basin margin (Cremaschi, 1987;
138 Garzanti et al., 2011) and from isolated hills in the alluvial plain, generated by South-Alpine (Zerboni
139 et al., 2015) and Apennine blind thrusts (Zuffetti et al., 2018). In depocentral areas, mature paleosols
140 are replaced by sequences of aggradationally stacked, weakly developed paleosols laterally
141 traceable for tens of km (Amorosi et al., 2017a). A series of closely spaced paleosols, marking the
142 MIS 3/MIS 2 transition, has been described as the equivalent of the Interfluve Sequence Boundary
143 (McCarty and Plint, 2003) in a high accommodation setting, due to its peculiar geometric

relationships with genetically related fluvial-channel bodies (Amorosi et al., 2017a). The most widespread paleosol reported in the Po Plain marks the Pleistocene-Holocene boundary and responds to several local names: 'Caranto' in the Venetian Plain (Mozzi et al., 2003), 'Ringhiera paleosol' in the Romagna area (Ravazzi et al., 2006), 'YD paleosol' in the Po Delta Plain (Amorosi et al., 2017b; Morelli et al., 2017), 'PH paleosol' in the Bologna urban area (Amorosi et al., 2014; Bruno et al., 2020b; this name will be used in this paper). Although a wide literature reported the existence of this pedogenized horizon, the mechanisms and causes of its formation and burial are not yet fully understood. More discontinuous paleosols have been described from the Holocene succession (Bruno et al., 2015, 2013).

153

154

155 **3. METHODS**

156

This work is based on the sedimentological and stratigraphic analysis of core material. Sixty-nine cores, 30-50 m deep (red circles in Fig. 2), were analysed and sampled for radiocarbon dating. For each core lithology, grainsize, colour and accessory materials (vegetal and shell macrofossils, carbonate concretions, redoximorphic features) were reported. The reaction to HCl was tested as a qualitative indicator of the presence of calcium carbonate. Resistance was measured on fine-grained sediments with a Pocket Penetrometer (PP). One hundred and seventy-two wood, peat, vegetal-remains and bulk-soil samples were dated at the KIGAM AMS laboratory (Daejeon, Republic of Korea) and at the Ion Beam Physics laboratory of the ETH (Zurich, Switzerland, Synal et al., 2007). Samples were collected fresh from the innermost part of the core and desiccated in a 40° oven. The humin fraction was separated through acid-alkali-acid (AAA) pre-treatment and AMS dated. Humic

166

167 acids, extracted from 9 bulk soil samples were also dated. Conventional ^{14}C ages were calibrated
168 using OxCal 4.4, with the IntCal 20 curve (Reimer et al., 2020).

169 More than 100 core descriptions from previous works and from the database of the Geological,
170 Seismic and Soil survey of Regione Emilia-Romagna (yellow circles in Fig. 2) were reinterpreted
171 following calibration with new cores. These descriptions provide information on lithology, colour,
172 consistency, reaction to 10% HCl, pocket penetrometer measurement and radiocarbon dates.
173 Additional 204 radiocarbon dates derive from previously published works (Geological Map of Italy
174 to scale 1:50.000; Ravazzi et. al., 2006; Cacciari et al., 2017; Marabini and Vai, 2020).

175

176

177 **4. RESULTS**

178

179 **4.1. Sedimentary facies**

180

181 The sedimentological analysis of the studied cores led to the identification of several facies
182 associations which belong to alluvial, deltaic, estuarine and shallow-marine depositional
183 environments. To the purposes of this paper, we will describe in detail four main facies associations,
184 which are part of the alluvial, upper delta-plain and inner estuary depositional systems. For other
185 facies associations, the reader is referred to Amorosi et al. (2017b, 2019) and Bruno et al. (2017).

186

187 **4.1.1. Fluvial channel-related facies association (FCR)**

188

189 This facies association is composed of cross-stratified or laminated coarse-to-fine sand with local
190 mud intercalations (Fig. 3). The occasional presence of floated woods or plant debris is recorded.

191 Marine or lagoonal macrofossils are absent, whereas shell fragments of freshwater gastropods
192 are seldom encountered.

193 Based on lithology, sedimentary structures and on the lack of marine and lagoonal macrofossil,
194 these coarse-grained deposits are interpreted as related to fluvial activity (in-channel deposition,
195 bar migration, crevassing, proximal overbank; Miall, 1985; Toonen et al., 2012; Aslan, 2013).

196

197 4.1.2. Freshwater swamp and marsh (SM)

198

199 This facies association is dominated by fine-grained material, with abundant wood, vegetal
200 remains and peat (Fig. 3). Peat horizons, 5-30 cm thick, are composed of poorly decomposed woody
201 material and are separated by grey (2.5 YR 7.1, 7.5 YR 8/1), peat-free clays. Freshwater fossils were
202 locally encountered. Consistency is very weak and PP values are $< 1 \text{ kg/cm}^2$. Carbonate concretions
203 and redoximorphic features are absent. This facies association shows poor lateral extent in the
204 Upper Pleistocene succession. On the contrary, in Holocene distal deposits it is volumetrically
205 dominant and only locally interrupted by channel-related sands.

206 The grain size of this facies group denotes a low-energy depositional environment. The
207 abundance of poorly decomposed organic material and the lack of oxidation suggest the setting of
208 reducing conditions in submerged environments. The latter were likely isolated ponds during the
209 Late Pleistocene, and swamp-marshes part of wider delta-plain and bayhead delta systems during
210 the Holocene (Amorosi et al., 2017b; Bruno et al., 2017; Cacciari et al., 2020). Peat horizons
211 separated by peat-free clays testify to intermittent sedimentation, with peat accumulation during
212 sedimentation breaks (Hijma and Cohen, 2011; Ishii et al., 2016; Bruno et al., 2019).

213

214 4.1.3. Poorly drained floodplain (PDFP)

215

216 This facies association is composed of grey (7.5 YR 6/1) silty clays with faint lamination given by
217 millimetre-scale silt intercalations. Soft and isolated carbonate concretions (CC in Fig. 4) and sparse
218 plant debris (UOM in Fig. 4) were seldom encountered. Redoximorphic features are lacking.
219 Freshwater gasteropods were seldom encountered. Consistency is weak to firm. Pocket
220 penetrometer values are in the range of 1-2 kg/cm².

221 Based on grainsize and fossil content, this facies association is interpreted as deposited in a distal
222 fluvial environment, occasionally subjected to river flooding. Lack of redoximorphic features
223 suggests a groundwater table fluctuating close to the topographic surface (poorly drained
224 floodplain). The amount, distribution and type of secondary calcite are consistent with this
225 interpretation.

226

227 4.1.4. Well-drained floodplain (WDFP)

228

229 This facies association is composed of firm-to-hard clayey silts and silty clays. Sedimentary
230 structures are absent. By contrast, polygonal structures, desiccation cracks and rootlets are
231 commonly observed. A well-expressed horizonation is given by colour and CaCO₃ distribution (Fig.
232 3). Dark horizons, showing weak or no reaction to HCl alternate with lighter horizons showing strong
233 reaction to HCl. Carbonate concretions, in the form of coalescent nodules, coatings, filaments and
234 sub-horizontal bands are observed in lighter horizons. Redoximorphic features, in the form of
235 orange mottles or bands (RF in Fig. 6), are commonly observed at the mesoscale. Plant debris and
236 freshwater gasteropods are seldom encountered. PP values are > 2 kg/cm².

237 As for facies PDFP, grainsize and fossil content point to a distal fluvial environment, occasionally
238 inundated by river waters (Collinson, 1996). The alternation of dark and light horizons is interpreted

239 as the result of multiple phases of soil development interrupted by overbank deposition and
240 paleosol burial. Dark colour reflects the accumulation and decomposition of organic matter in the
241 topsoil (Bruno et al., 2020b). Carbonate distribution, with carbonate-free horizons overlying CaCO_3
242 enriched horizons, is interpreted as the result of carbonate leaching from the topsoil (A horizon)
243 and illuviation to the underlying Bk horizon (Boul et al., 2011). Carbonate mobilization requires the
244 percolation of meteoric waters in a vadose zone. We, thus, argue that the groundwater was located
245 a few metres below the topographic surface during subaerial exposure (well-drained floodplain).

246

247

248 **4.2. Paleosol stratigraphy**

249

250 Paleosols were identified at three stratigraphic intervals in the Upper Pleistocene-Holocene
251 succession of the Po Plain.

252 The lower interval is composed of a series of closely-spaced paleosols (paleosols P in Figs. 4, 5
253 and 6), whose cumulative thickness is in general < 5 m. Calibrated ages span from the ^{14}C detection
254 limit (~ 50 kyr B.P.) to ~ 23 kyr B.P. (Figs. 5 and 6). These paleosols show A-Bk-Bw or A-Bk profiles. A
255 horizons, 30-50 cm thick, are decalcified (Bruno et al., 2020b; Amorosi et al., this volume) and
256 present diffuse organic matter (DOM in Fig. 4) and slight bands of Fe oxides and/or hydroxides (Fig.
257 3). Undecomposed organic matter was not observed and carbonate concretions have locally been
258 reported from the base and the top of these horizons. Bk horizons are typified by high CaCO_3 content
259 (30-40% of the total volume, Bruno et al., 2020b). Carbonate concretions are abundant as
260 coalescent nodules or whitish sub-horizontal bands (evolutionary stage II of Gile et al., 1981;
261 Machette, 1985). Transition to overlying and underlying horizons is in general gradational. Bw
262 horizons show moderate CaCO_3 content (Bruno et al., 2020b; Amorosi et al., this volume) and faint

263 mottles of Fe oxides and-or hydroxides. Evidences of clays mobilization (Bt horizons) were not
264 observed. At distal locations, these paleosols may show less clear horizonation (A-Bw profile) or may
265 be replaced by coeval peat-bearing swamp deposits (Fig. 5).

266 In the second interval, a single paleosol (paleosol PH, Figs. 4, 5 and 6) is encountered at the top
267 of a 3-10 m thick sedimentary unit composed of overbank muds and subordinated channel-related
268 sands (Last Glacial Maximum Sedimentary Unit, LGM SU in Figs. 4, 5 and 6). Textural characters of
269 paleosol PH vary from proximal to distal locations. At inland locations (core EM15, Fig. 3), paleosol
270 PH shares many characteristics with older P paleosols: (i) a carbonate-free, brown (10YR 4/4, 3/3) A
271 horizon, up to 100 cm thick, with DOM and RF; (ii) a lighter Bk horizon with abundant nodules or
272 bands of secondary calcite (evolutionary stage II); (iii) a Bw horizon showing evidence of incipient
273 alteration. At more distal locations (cores EM1 and EM3, Fig. 3), paleosol PH exhibit a grey (5Y 4/1,
274 2.5Y 6/1) decalcified A horizon, 30-50 cm thick, with DOM. Plant debris, absent in the lower part,
275 become increasingly abundant upsection and, at places, grade into the overlying peats (see core B3,
276 Fig. 4). The underlying Bk horizon, when present, is relatively thin (a few dm), with secondary calcite
277 in the form of nodules, coatings or filaments (evolutionary stages I and II). Redoximorphic features
278 were not observed at the mesoscale along the whole soil profile.

279 In the third interval, dated to the Holocene, paleosols (H1 and H2 in Figs. 4, 5 and 6) have been
280 observed only at inland locations. At distal locations, they are replaced by coeval estuarine and
281 deltaic deposits. H paleosols have poor correlation potential and their textural features vary
282 dramatically from a place to another, without specific spatial trends. In few localities, they show
283 characteristics similar to those of their Pleistocene counterparts. At places, they are barely
284 identifiable due to a poorly developed horizonation. Archeological artifacts are increasingly
285 abundant in younger paleosols.

286 Paleosols P and PH bound nearly tabular sediment packages and are locally replaced by coeval
287 incisions filled with FCR or SM deposits (see cores CNT, RN3 and EM2, Fig. 5). On the contrary,
288 Holocene paleosols overlie or are overlain by CR facies (see cores MW and 15, Figs. 5 and 6). Alluvial
289 units delimited by these soil horizons are poorly extended and typically wedge out laterally or
290 downdip (Figs. 5 and 6).

291

292

293 **4.3. Radiocarbon dating of paleosols**

294

295 Upper Quaternary successions provide the great opportunity to link pedo-sedimentary events to
296 the detailed climatic and eustatic history described in a vast literature (eg. Clark and Huybers, 2009;
297 Lambeck et al., 2011; Rasmussen et al., 2014). Assessing the timing of soil development and burial
298 is crucial to disentangle the relative influence of global and local factors. This chapter summarizes
299 observations deriving from the analysis of a chronological database composed of 376 radiocarbon
300 dates (160 from paleosols).

301 Along single cores, multiple dating of A horizons yielded stratigraphically ordered ages, spanning
302 3-5 kyr (see cores B3, RW28 and 13, Figs. 4, 5C and 6). Only in core SPR (Fig. 5C) two samples from
303 the base and the top of the same A horizon provided similar ages. In distal cores, plant debris from
304 topmost A horizons yielded ages that are considerably younger (up to 5 kyr) than those from bulk-
305 soil samples and just a few centuries older than those from overlying SM peats (see cores EM1, EM3
306 and B3, Figs. 3, 4 and 5). Dates from A horizons indicate aggradation at extremely low rates (0,05-
307 0,23 mm yr⁻¹) during soil development. Accumulation rates above or between paleosols are at least
308 one order of magnitude greater (> 1 mm/yr). Distinct ages were also obtained from different

309 fractions extracted from the same sample. Particularly, humic acids yielded, in 9 cases out of 10,
310 ages older than those obtained from the humin fraction (Table 1).

311 Dates from bulk-soil samples change also laterally, along the same paleosol, spanning in a range
312 of 4-6 kyr (Fig. 3). No specific trend was observed from proximal to distal locations. Ages also change
313 over short distances, as observed in the Bologna area. In the Two Tower Medieval district, where
314 distance between cores is just 10-20 m, six samples from paleosol P3 yielded ages in the range of 3-
315 4 kyr (Fig. 6).

316 The frequency distribution of radiocarbon dates from paleosols (grey rectangles in Fig. 7) shows
317 a major peak between 14 and 10 kyr B.P., related to the PH paleosol. Samples from the P paleosols
318 yielded ages clustered around three minor peaks (P1, P2 and P3, Fig. 7), at 46-41, 38-32 and 29-25
319 cal kyr B.P., respectively. The overall decay with time in the number of ^{14}C dates across the
320 Pleistocene simply reflects the fact that older sediments were penetrated by a progressively lower
321 number of cores. A decline in the number of ^{14}C dates from soil samples is also recorded towards
322 younger ages, together with a sharp increase in dates from SM and PDFP deposits. Ages from
323 Holocene soil samples are clustered around two peaks. The older peak reflects, in part, the youngest
324 ages from paleosol PH and in part dates from a distinct paleosol (H1 in Figs 4, 5 and 6) observed at
325 several inland locations. In the Bubano Quarry (BQ in Fig. 5C), 5 m-thick overbank strata separate
326 H1 from PH. In the Bologna area (core 16, Figs. 4 and 6), paleosol H1 bears Neolithic and Eneolithic
327 artefacts (Bruno et al., 2013). The second peak (H2, Fig. 7) corresponds to another archeological
328 level, rich in Late Bronze Age, Iron-Age and Roman rests (IR paleosol of Bruno et al., 2013), which
329 was buried in large part of the Po Plain during the Middle Ages (see core CRV, Fig. 5A). Locally, this
330 paleosol is still exposed (Fig. 5). Interestingly, the maximum number of ^{14}C dates from facies FCR is
331 recorded between H2 and H1.

332

5. DISCUSSION

5.1 Use and limitations of radiocarbon for the estimation of the exposure age of paleosols

The use and reliability of radiocarbon dates from paleosols have been widely debated because, unlike plant macrofossils, which preserve the particular ^{14}C content of the moment of grow, soils are open systems where organic carbon is continuously incorporated, humified and-or oxidized to CO_2 before burial (Orlova and Panychev, 1993; Martin and Johnson, 1995; Gaudinski et al., 2000). Therefore, ^{14}C ages from paleosols reflect the mean residence time of the organic carbon plus the time of burial (Matthews, 1980; Geyh et al., 1983). The amount of organic carbon added to a soil and the velocity of its transformation processes change from place to place as a function of climate, vegetation and parent material (Reimer et al., 2020). Moreover, turnover and breakdown of organic matter may lead to the redistribution of ^{14}C ratios in different soil fractions. As a result, apparently conflicting ages can be obtained from the same paleosol (Figs. 5 and 6) and from different soil fractions (Table 1). Because of this inherent variability, many authors concluded that radiocarbon dates from soils are unreliable and the concept of “age” cannot be strictly applied to paleosols (Gilet-Blein et al., 1980; Becker-Heidmann et al., 2002). However, if not subjected to post-burial contamination (e.g. rootlets), paleosols should yield ages scattered within its formation period. The estimation of the length of this period, which can attain several millennia, is an intriguing goal for Quaternary paleosol stratigraphers.

The lack of evidence of clay mobilization, the evolutionary stage of secondary calcite and the limited rubefaction suggest that Po Plain paleosols evolved over relatively short periods. Radiocarbon ages from deposits below and above paleosols constrain their exposure period within

10-12 thousand years (Figs. 5 and 6). Dates from paleosols are within the narrower range of 4-6 millennia and provide a robust constrain for stratigraphic correlations over long distances (Amorosi et al., 2017a). More complex is the precise assessment of the ages that mark the onset and end of pedogenesis for each paleosol, even if radiocarbon dates are available from the base and top of A horizons. Previous work has demonstrated that, although some organic carbon can remain in soils for millennia (Feng, 2009), the oldest organic fraction accumulated at the onset of pedogenesis may have been completely replaced by younger organic carbon (Scharpenseel, 1971; Alexandrovskiy and Chichagova, 1998) introduced by roots in the deepest soil horizons. Thereby, radiocarbon dates from organic-sediment samples collected from the base of the A horizon may not be representative of the onset of soil formation (Gilet-Blein et al., 1980; Alexandrovskiy and Chichagova, 1998). Several factors influence carbon turnover times in soils (Kleber, 2010; Chen et al., 2013; Pandey et al., 2014). Particularly, carbon renewal is slower in colder climates and in deep soil horizons (Alexandrovskiy and Chichagova, 1998; Gaudinski et al., 2000; Fontaine et al., 2007). Therefore, for soils that developed in cold climatic conditions, such as paleosols P3, which formed at the onset of Last Glacial Maximum, dates from the base of the A horizon should better approximate the onset of pedogenesis. This assumption is corroborated by dates from core B3 (Figs. 3, 4 and 5), where the oldest age from paleosols P3 partially overlaps the age from underlying paleosol P2. For paleosols developed in warmer periods (PH and H paleosols), ages from the base of A horizons may post-date the onset of pedogenesis.

Sediment samples collected from the top of A horizons may be older than burial time, because a certain amount of time is required for litter humification and mineralization (Chichagova and Cherkinsky, 1993). At inland locations of our study area, where O horizons are generally not preserved, burial ages cannot be assessed precisely. Available dates permit to assert, for example, that paleosol PH was buried after 10.3 kyr B.P. in core 13 (Figs. 4 and 6) and between 14.3 and 8.6

kyr B.P. in core 201S4 (Fig. 5). Conversely, at distal locations, plant macrofossils preserved in the topsoil provides ages that approximate the paleosol burial age with an error of a few centuries. For example, in EM1, where estuarine sedimentation was already established around 8.1 kyr B.P., burial of paleosol PH occurred around 8.5 kyr B.P. (Figs. 3, 4 and 5).

Age/depth gradients, like those observed in the Po Plain paleosols, have been reported from several soil profiles (Matthews, 1981; Matthews and Dresser, 1983; Alexandrovskiy and Chichagova, 1998; Becker-Heidmann et al., 2002) and can possibly be explained by the fact that the amount of carbon added to the topsoil through litter accumulation is in general order of magnitudes greater than the one introduced in deeper soil horizons via roots exudation (Fontaine et al., 2007). The measured accumulation rates, incompatible with alluvial sedimentation, suggest that litter accumulation accounted for soil aggradation during exposure, with a possible contribution of wind-transported dust. Therefore, paleosols from the Po Plain represent condensation horizons, rather than depositional hiatuses. On the contrary, sedimentation between pedogenetic phases seems a quasi-instantaneous process (see ages from P2 and P3 in core B3, Figs 4 and 5). Paleosols aggradation is also testified by the presence of carbonate concretions in lower A horizons, likely related to the upward migration of the eluvial-illuvial (A-B) boundary, and by vertically stacked sub-horizontal bands of secondary calcite in Bk horizons (Fig. 3). Carbonate concretions in upper A horizons, on the other hand, reflect post-burial illuviation from overlying paleosols. For this reason, we avoided radiocarbon dating of carbonates and removed secondary calcite in acid steps of the AAA sample preparation, before AMS analysis. Humic acids are also considered as a mobile compound, which may yield anomalously young ages due to contamination from overlying strata (Matthews, 1980). In our case, the oldest ages are provided by humic acids (Table 1). We thus excluded contamination from overlying strata during each phase of pedogenesis.

404

5.2. Pedo-sedimentary evolution of the Po Plain and controlling factors

With the chronological constraint of 376 radiocarbon dates, the alluvial succession of the southern Po Plain provides an unprecedented record of pedo-sedimentary events across the last 50 kyr.

Aggradationally stacked paleosols 'P' developed during the Late Pleistocene, when the Adriatic coastline migrated in response to the stepwise sea-level fall toward its lowstand position, ~300 km away from the modern one (Pellegrini et al., 2018). Among P paleosols, only P3 developed during a phase of sea-level drop (~30–50m between 30 and 24 cal ka BP, Peltier and Fairbanks, 2006; Fig. 7B). Conversely, P1 and P2 developed in a period characterized by low-amplitude sea-level oscillations (Chappell, 2002; Fig. 7B). Far from the influence of sea-level change, pedo-alluvial processes are controlled by the balance between sediment supply and water discharge (Blum and Törnqvist, 2000). Low sediment supply-discharge ratios result in channel incision and soil development in the adjacent interfluvies, whereas high sediment supply-discharge ratios promote fluvial aggradation and paleosol burial (Demko et al., 2004). Bruno et al. (2020b) documented that soil development and burial during the Late Pleistocene was mainly controlled by changes in vegetation driven by climatic oscillations at the scale of Bond cycles (Bond et al., 1993). Soils started to form at the onset of Bond cycles, when warm climate conditions favoured the spread of dense forests (Magri, 1999; Fletcher et al., 2010), which protected the Apennine drainage basins from erosion (low sediment supply). Soil development was systematically interrupted during the subsequent cold phases, at the culmination of Bond cycles, corresponding to North Atlantic Heinrich events (light blue vertical lines in Fig. 7B). These periods record generalized forest retreats (Fletcher et al., 2010; Helmens, 2014), which enhanced erosion in the drainage basins and sediment transfer to the alluvial plains. Increased sediment supply promoted the filling of fluvial incisions and the

430 burial of formerly exposed interfluvies by overbank sedimentation. Thin sediment packages were
431 deposited between two successive phases of subaerial exposure (Figs. 3 to 6). These deposits (and,
432 partly, the underlying paleosols) were modified during the successive pedogenetic phase. A similar
433 response to millennial-scale climate oscillations has been observed in loess paleosol-bearing
434 successions (Rousseau et al., 2011, 2007; Moine et al., 2017; Zeeden et al., 2018).

435 The Last Glacial Maximum was characterized by deposition of thick and widespread fluvial-
436 channel gravel-sand bodies in the Po Plain (Ravazzi et al., 2012; Campo et al., 2016) and in other
437 alluvial systems worldwide (Lewis et al., 2001; Briant et al., 2005). Alpine glaciers, which extended
438 down to the Po Plain margin, supplied huge amounts of sediments to the related fluvio-glacial
439 systems (Fontana et al. 2014). In the Apennine domain, high sediment supply, favoured by a
440 predominantly herbaceous vegetation cover of drainage basins (Vescovi et al., 2010), resulted in the
441 deposition of the LGM SU, which bears poor evidence of pedogenesis (Figs. 4, 5 and 6).

442 Above the LGM SU, PH is the most widespread paleosol in the Po Plain. This surface yielded
443 radiocarbon dates spanning between ~17 and 6 kyr B.P. (Fig. 8), but mostly clustered around 14 and
444 10 kyr B.P. (Fig.7). The precise assessment of the age of PH formation is hampered by paucity of
445 dateable material from the underlying LGM SU. However, available dates indicate that the onset of
446 post-LGM pedogenesis was diachronous across the Po Plain, without a specific spatial trend (Fig. 8).
447 Whereas in the Bologna area PH started to develop at least 16.8 kyr B.P. (see core RW28, Figs 6 and
448 8), in the Romagna plain (Bubano Quarry - BQ, in Figs 5C and 8) pedogenesis started after 14.4 kyr
449 B.P. (Ravazzi et al., 2006). We argue that post-LGM pedogenesis was favoured by decreased
450 sediment supply related to the progressive afforestation of the area (Pini et al., 2010; Vescovi et al.,
451 2010; Campo et al., 2020), with diachroneity possibly related to particular local conditions (e.g.
452 distance from active channels). North of the Po River, in the Alpine tributary system, fluvial incision

453 occurred soon after glacial retreat (~17 kyr B.P., Monegato et al., 2017), due to sediment trapping
454 in lakes which formed in place of abandoned glacial amphitheatres (Fontana et al., 2014).

455 Interestingly most of the ^{14}C dates from paleosol PH post-date the Oldest Dryas (OD in Fig. 7).
456 The clustering of dates around the Younger Dryas in the Po delta plain (Figs. 7A and 8), suggested a
457 possible control of this cold event on paleosol formation (Amorosi et al., 2017b, Morelli et al., 2017).
458 The wider dataset shown in this work highlights that pedogenesis started in many sites of the Po
459 Plain at least during the Bølling and Allerød warm phases (BA in Fig. 7A). Unlike cold phases at the
460 culmination of pre-LGM Bond cycles, the Younger Dryas cold spell did not lead to paleosol burial.
461 This event was probably too short-lived to promote the filling of fluvial incisions and overbank
462 sedimentation. Paleosol development recorded after LGM in other alluvial (Mol, 1997; Choi, 2005;
463 van Balen et al., 2010; Janssens et al., 2012) and eolian (Kaiser et al., 2009; Hošek et al., 2017)
464 successions, indicates a likely climate control at a supra-regional spatial scale. Progressively warmer
465 conditions lead to widespread afforestation and reduced sediment supply (Fletcher et al., 2010;
466 Helmens, 2014).

467 Whereas Alpine rivers still flow entrenched in Pleistocene deposits, Apennine incisions were filled
468 during the Early Holocene (see cores RN3 and EM2, Fig. 3C) and paleosol PH was buried soon after.
469 In the coastal plain, where paleosol PH is encountered at greater depths beneath estuarine deposits,
470 burial ages show an overall inverse power law with elevation (Fig. 9) that reflects the progressive
471 drowning of the area during the early Holocene sea-level rise (Bruno et al., 2017). Slight dispersion
472 of data may reflect post-burial deformation of paleosol PH by differential subsidence and
473 neotectonics (Amorosi et al., 2021). In the area under marine influence (shades of blue in Fig. 10),
474 burial ages decrease landwards from ~11.5 to 5.4 kyr B.P.. This overall spatial trend is not recorded
475 in two isolated areas, where paleosol PH and older paleosols are upbended (see also Fig. 5C). In
476 cross-sections, the progressive drowning of paleosol PH is testified by onlap terminations of

477 Holocene flooding surfaces (Fig. 5A). These horizons, associated to prominent facies backstepping,
478 are coeval to the main Holocene melt water pulses (MWP-1b, 1c, 1d; Fig. 7B), which forced the
479 landward migration of the Po estuary across the study area. The effects of MWP-1A are not recorded
480 in the study area, which was too far from the coastline at that time (Storms et al., 2008).

481 Pedo-sedimentary features of paleosol PH reflect this evolutionary history. Carbonate
482 redistribution along the soil profile and relatively low amounts of organic carbon in the A horizons
483 (Amorosi et al., this volume) are indicative of a low groundwater table (Kalisz et al., 2010), enhanced
484 by fluvial incision during the early phases of soil development (Tebbens et al., 1999). Preserved plant
485 debris in the topsoil, radiocarbon dated to the early Holocene (Figs. 4 and 5), reflects the progressive
486 rise in groundwater table (Bohacs and Suter, 1997) up to the setting of waterlogged conditions and
487 to the accumulation of peat beds (Diessel, 1992; Richardson and Vepraskas, 2001; Stolt and
488 Rabenhorst, 2011). The rise of the groundwater table, forced by sea-level rise (Kosters and Suter,
489 1993; Törnqvist, 1993; Wadsworth et al., 2003), led to the progressive filling of Apennine fluvial
490 incisions by fine-grained and organic-matter-rich estuarine strata (facies SM, cores RN3 and EM2 in
491 Fig. 5C). The lack of fluvial sands (facies FCR) at the base of fluvial incisions, suggests that valley
492 filling was promoted by eustasy rather than by an upstream increase in sediment supply (Kvale and
493 Archer, 2007).

494 Beyond the area of marine influence, at elevations > -3 m, the burial age of paleosol PH is
495 substantially unpredictable (Figs. 9 and 10). The dispersion of burial dates in this upstream sector
496 reflects the dynamics of Holocene sedimentation, dominated by avulsion processes and by the
497 deposition of poorly extended alluvial units (Figs. 5 and 6). This aspect is particularly evident in the
498 Bologna area (Fig. 6): in core 16, for example, paleosol PH was already buried around 8.2 kyr B.P.,
499 when paleosol H1 was still developing (see also Fig. 4); in the nearby core 15, at a distance of just
500 224 m, the burial of paleosol PH occurred only around 7 kyr B.P.. The transition to an avulsive

501 sedimentation pattern at the onset of the Holocene, recorded in several worldwide fluvial systems
502 (Phillips, 2011; Stouthamer et al., 2011), is an indirect consequence of the landward migration of
503 the coastline, which dramatically reduced the area available for sediment storing and lowered rivers
504 longitudinal gradients. Decreased stream power, and capability to erode banks and create space for
505 sediment storage, led to river aggradation, crevassing and avulsions (Blum et al., 2013).

506 The discontinuity of Holocene paleosols (Figs. 5 and 6) reflects the limited areal extent of the
507 sedimentary units on which they developed. Avulsive sedimentation patterns and crevassing also
508 determined laterally variable maturity of Holocene paleosols. Indeed, soil development was
509 interrupted only in restricted areas affected by alluvial deposition. In sediment-starved areas, soils
510 continued to evolve. Lateral changes in soil maturity are observable in modern soils, which started
511 to develop during the Late Bronze age (areas where H2 is still exposed – Fig. 5), and after the Middle
512 Ages (areas where H2 is buried - Fig. 5).

513 The peak in radiocarbon dates from fluvial channel-related deposits, centred around 5-6 kyr B.P.
514 (Fig. 7), corresponds to a generalized re-organization of the river network at the onset of
515 Neoglaciation (Piovan et al., 2012; Bruno et al., 2015; Amorosi et al., 2017b), which led to the burial
516 of paleosol H1. Slope instability and enhanced sediment production, recorded in the Northern
517 Apennines since 5.5 kyr B.P. (Soldati et al., 2006; Picotti and Pazzaglia, 2008), likely reflect
518 widespread deforestation of the Apennine drainage basins during the early Eneolithic (Cremaschi
519 and Nicosia, 2012). The progressive return to stable floodplain conditions was paralleled by
520 improved techniques of land reclamation and management from the late Bronze age to late
521 Antiquity (Bruno et al., 2013).

522

523

524 6. CONCLUSIONS

525

526 Based on the sedimentological analysis and correlation of more than 170 core data, with the
527 chronological constraint of 376 radiocarbon dates, this study provided new data on: (i) the complex
528 relationships between pedogenetic, fluvial and costal processes in alluvial and paralic environments;
529 (ii) the relative influence of global (i.e. climate and eustasy) and local (e.g. river avulsions) factors on
530 soil development and burial; (ii) the use and limitations of radiocarbon to assess the exposure age
531 of paleosols.

532 In the Upper Pleistocene-Holocene mud-prone succession of the Po Basin, vertically stacked,
533 weakly developed paleosols testify to intermittent pedogenesis, periodically interrupted by
534 overbank sedimentation. Radiocarbon analyses permitted to define the duration of the main phases
535 of pedogenesis and to compare them to climate and eustatic curves.

536 Radiocarbon dates from paleosols (bulk-soil and plant-debris samples) and from underlying and
537 overlying sedimentary units indicate exposure periods encompassing 4-6 millennia. This estimate is
538 consistent with pedological features (e.g. type of secondary calcite, lack of illuvial clay, limited
539 rubefaction), which denote incipient pedogenesis. Stratigraphically ordered ¹⁴C calibrated ages
540 within A horizons revealed that Po Plain paleosols are condensation horizons, which experienced
541 slow aggradation during exposure (0,05-0,23 mm/yr) due to accumulation of plant litter, with a likely
542 contribution of wind-transported dust.

543 Millennial-scale climate oscillations and glacio-eustasy concurred in driving the pedo-
544 sedimentary evolution of the Po Plain during the Late Pleistocene. In particular, during the MIS 3,
545 pedogenetic events were mainly controlled by changes in vegetation driven by climatic oscillations
546 at the scale of Bond cycles. Paleosols developed in well-drained floodplain environments, dissected
547 by fluvial incision, during relatively warm periods. Overbank sedimentation and paleosol burial

548 occurred during colder phases. During the Last Glacial Maximum, high-sediment-supply hindered
549 pedogenesis and led to the accumulation of 3-10 m-thick overbank strata.

550 Widespread soil development (paleosol PH) occurred at the end of the Last Glacial Maximum,
551 following glaciers retreat and afforestation of drainage basins. Burial of paleosol PH was
552 diachronous as indicated by radiocarbon dates from vegetal remains preserved at the topsoil. At
553 distal locations, paleosol PH was progressively drowned and buried under estuarine sediments
554 during the Holocene phases of post-glacial sea-level rise. Beyond the area of marine influence, burial
555 ages of paleosol PH change from a place to another without specific spatial trends, reflecting
556 upstream fluvial sedimentation dominated by avulsions.

557 Holocene (H) paleosols, observed at inland locations, grade seaward into coeval estuarine and
558 deltaic deposits. These pedogenized horizons show a poor correlation potential and laterally
559 variable degree of maturity that reflect avulsive sedimentation patterns and widespread crevassing.
560 Human activities (e.g. deforestation and land reclamation) became an increasingly important factor
561 affecting pedo-sedimentary processes during the last 6 kyr.

562 This study highlights the potential for paleoenvironmental reconstructions of upper Quaternary
563 sedimentary successions. The pedo-stratigraphic approach adopted here, relying upon a robust
564 chronological framework, permitted to assess the temporal and spatial scale of pedogenetic events
565 and to discern the relative contribution of distinct controlling factors that typically act
566 contemporaneously.

567

568

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REFERENCES

- Aitken, J.F., Flint, S.S., 1996. Variable expressions of interfluvial sequence boundaries in the Breathitt Group (Pennsylvanian), eastern Kentucky, USA. *Geol. Soc. London, Spec. Publ.* 104, 193–206.
- Alexandrovskiy, A.L., Chichagova, O.A., 1998. Age of humic substances in paleosols. *Radiocarbon* 40, 991–997.
- Amadori, C., Toscani, G., Di Giulio, A., Maesano, F.E., D’Ambrogi, C., Ghielmi, M., Fantoni, R., 2019. From cylindrical to non-cylindrical foreland basin: Pliocene–Pleistocene evolution of the Po Plain–Northern Adriatic basin (Italy). *Basin Res.* 991–1015. <https://doi.org/10.1111/bre.12369>
- Amorosi, A., Bruno, L., Rossi, V., Severi, P., Hajdas, I., 2014. Paleosol architecture of a late Quaternary basin – margin sequence and its implications for high-resolution , non-marine sequence stratigraphy. *Glob. Planet. Change* 112, 12–25. <https://doi.org/10.1016/j.gloplacha.2013.10.007>
- Amorosi, A., Bruno, L., Cleveland, D.M., Morelli, A., Hong, W., 2017a. Paleosols and associated channel-belt sand bodies from a continuously subsiding late quaternary system (Po basin, Italy): New insights into continental sequence stratigraphy. *Bull. Geol. Soc. Am.* 129, 449–463. <https://doi.org/10.1130/B31575.1>
- Amorosi, A., Bruno, L., Campo, B., Morelli, A., Rossi, V., Scarponi, D., Hong, W., Bohacs, K.M., Drexler, T.M., 2017b. Global sea-level control on local parasequence architecture from the Holocene record of the Po Plain, Italy. *Mar. Pet. Geol.* 87, 99–111. <https://doi.org/10.1016/j.marpetgeo.2017.01.020>

596 Amorosi, A., Barbieri, G., Bruno, L., Campo, B., Drexler, T.M., Hong, W., Rossi, V., Sammartino, I.,
 597 Scarponi, D., Vaiani, S.C., 2019. Three-fold nature of coastal progradation during the
 598 Holocene eustatic highstand, Po Plain, Italy—close correspondence of stratal character with
 599 distribution patterns. *Sedimentology* 66, 3029–3052.

600 Amorosi, A., Bruno, L., Campo, B., Costagli, B., Hong, W., Picotti, V., Vaiani, S.C., 2021. Deformation
 601 patterns of upper Quaternary strata and their relation to active tectonics, Po Basin, Italy.
 602 *Sedimentology* 68, 402–424. <https://doi.org/10.1111/sed.12784>

603 Amorosi, A., Bruno, L., Campo, B., Di Martino, A., I. Sammartino. Patterns of geochemical variability
 604 across weakly developed paleosol profiles and their role as regional stratigraphic markers (Late
 605 Pleistocene, Po Plain). Submitted to this volume.

606 Argnani, A., Barbacini, G., Bernini, M., Camurri, F., Ghielmi, M., Papani, G., Rizzini, F., Rogledi, S.,
 607 Torelli, L., 2003. Gravity tectonics driven by Quaternary uplift in the Northern Apennines:
 608 Insights from the La Spezia-Reggio Emilia geo-transect. *Quat. Int.* 101–102, 13–26.
 609 [https://doi.org/10.1016/S1040-6182\(02\)00088-5](https://doi.org/10.1016/S1040-6182(02)00088-5)

610 Aslan, A., 2013. Sediments. *Encycl. Quat. Sci. Second Ed.* 663–675. [https://doi.org/10.1016/B978-](https://doi.org/10.1016/B978-0-444-53643-3.00111-4)
 611 [0-444-53643-3.00111-4](https://doi.org/10.1016/B978-0-444-53643-3.00111-4)

612 Atchley, S.C., Nordt, L.C., Dworkin, S.I., 2004. Eustatic control on alluvial sequence stratigraphy: A
 613 possible example from the Cretaceous-Tertiary transition of the Tornillo Basin, Big Bend
 614 National Park, West Texas, U.S.A. *J. Sediment. Res.* 74, 391–404.
 615 <https://doi.org/10.1306/102203740391>

616 Becker-Heidmann, P., Andresen, O., Kalmar, D., Scharpenseel, H.W., Yaalon, D.H., 2002. Carbon
 617 dynamics in Vertisols as revealed by high-resolution sampling. *Radiocarbon* 44, 63–73.
 618 <https://doi.org/10.1017/S0033822200064687>

619 Benvenuti, M., Bonini, M., Moratti, G., Ricci, M., Tanini, C., 2008. Tectonic and climatic controls on

620 historical landscape modifications: The avulsion of the lower Cecina River (Tuscany, central
 621 Italy). *Geomorphology* 100, 269–284. <https://doi.org/10.1016/j.geomorph.2007.12.009>
 622 Blum, M.D., Törnqvist, T.E., 2000. Fluvial responses to climate and sea-level change: A review and
 623 look forward. *Sedimentology* 47, 2–48. <https://doi.org/10.1046/j.1365-3091.2000.00008.x>
 624 Blum, M., Martin, J., Milliken, K., Garvin, M., 2013. Paleovalley systems: Insights from Quaternary
 625 analogs and experiments. *Earth-Science Rev.* 116, 128–169.
 626 <https://doi.org/10.1016/j.earscirev.2012.09.003>
 627 Bohacs, K., Suter, J., 1997. Sequence stratigraphic distribution of coaly rocks: Fundamental
 628 controls and paralic examples. *Am. Assoc. Pet. Geol. Bull.* 81, 1612–1639.
 629 <https://doi.org/10.1306/7834e192-1721-11d7-8645000102c1865d>
 630 Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., 1992. andrews J. Huon S., Jantschik
 631 R., clasen S., Simet ch., Tedesco K., Klas M., Bonani G. Ivy S 245–249.
 632 Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonanl, G., 1993. Bond
 633 1993. *Nature* 365, 143–147.
 634 Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., DeMenocal, P., Priore, P., Cullen, H.,
 635 Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and
 636 glacial climates. *Science* (80-.). 278, 1257–1266.
 637 Boul, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2011. Soil genesis and classification:
 638 Hoboken, 6th ed. Wiley-Blackwell, Chichester. <https://doi.org/10.1002/9780470960622>.
 639 Briant, R.M., Bateman, M.D., Coope, G.R., Gibbard, P.L., 2005. Climatic control on quaternary
 640 fluvial sedimentology of a Fenland Basin river, England. *Sedimentology* 52, 1397–1423.
 641 <https://doi.org/10.1111/j.1365-3091.2005.00747.x>
 642 Bruno, L., Amorosi, A., Curina, R., Severi, P., Bitelli, R., 2013. Human-landscape interactions in the
 643 Bologna area (northern Italy) during the mid-late Holocene, with focus on the Roman period.

644 Holocene 23, 1560–1571. <https://doi.org/10.1177/0959683613499054>

645 Bruno, L., Amorosi, A., Severi, P., Bartolomei, P., 2015. High-frequency depositional cycles within
646 the late Quaternary alluvial succession of Reno River (Northern Italy). *Ital. J. Geosci.* 134, 339–
647 354. <https://doi.org/10.3301/IJG.2014.49>

648 Bruno, L., Bohacs, K.M., Campo, B., Drexler, T.M., Rossi, V., Sammartino, I., Scarponi, D., Hong, W.,
649 Amorosi, A., 2017. Early Holocene transgressive palaeogeography in the Po coastal plain
650 (northern Italy). *Sedimentology* 64, 1792–1816. <https://doi.org/10.1111/sed.12374>

651 Bruno, L., Piccin, A., Sammartino, I., Amorosi, A., 2018. Decoupled geomorphic and sedimentary
652 response of Po River and its Alpine tributaries during the last glacial/post-glacial episode.
653 *Geomorphology* 317, 184–198. <https://doi.org/10.1016/j.geomorph.2018.05.027>

654 Bruno, L., Campo, B., Di Martino, A., Hong, W., Amorosi, A., 2019. Peat layer accumulation and
655 post-burial deformation during the mid-late Holocene in the Po coastal plain (Northern Italy).
656 *Basin Res.* 31, 621–639. <https://doi.org/10.1111/bre.12339>

657 Bruno, L., Campo, B., Costagli, B., Stouthamer, E., Teatini, P., Zoccarato, C., Amorosi, A., 2020a.
658 Factors controlling natural subsidence in the Po Plain. *Proc. Int. Assoc. Hydrol. Sci.* 382, 285–
659 290. <https://doi.org/10.5194/piahs-382-285-2020>

660 Bruno, L., Marchi, M., Bertolini, I., Gottardi, G., Amorosi, A., 2020b. Climate control on stacked
661 paleosols in the Pleistocene of the Po Basin (northern Italy). *J. Quat. Sci.* 35, 559–571.
662 <https://doi.org/10.1002/jqs.3199>

663 Burrato, P., Ciucci, F., Valensise, G., 2003. An inventory of river anomalies in the Po Plain, Northern
664 Italy: Evidence for active blind thrust faulting. *Ann. Geophys.* 46, 865–882.
665 <https://doi.org/10.4401/ag-3459>

666 Cacciari, M., Cremonini, S., Marchesini, M., Vianello, G., Antisari, L.V., 2017. When a pedomarker is
667 lacking: palynological and chemical multianalysis of a lateglacial-holocene soils suite

668 (Bologna). *EQA-International J. Environ. Qual.* 24, 47–73.

669 Cacciari, M., Amorosi, A., Marchesini, M., Kaniewski, D., Bruno, L., Campo, B., Rossi, V., 2020.

670 Linking Holocene vegetation dynamics , palaeoclimate variability and depositional patterns in

671 coastal successions : Insights from the Po Delta plain of northern Italy. *Palaeogeogr.*

672 *Palaeoclimatol. Palaeoecol.* 538, 109468. <https://doi.org/10.1016/j.palaeo.2019.109468>

673 Campo, B., Amorosi, A., Bruno, L., 2016. Contrasting alluvial architecture of Late Pleistocene and

674 Holocene deposits along a 120-km transect from the central Po Plain (northern Italy).

675 *Sediment. Geol.* 341, 265–275.

676 Campo, B., Bruno, L., Amorosi, A., 2020. Basin-scale stratigraphic correlation of late Pleistocene-

677 Holocene (MIS 5e-MIS 1) strata across the rapidly subsiding Po Basin (northern Italy). *Quat.*

678 *Sci. Rev.* 237, 106300. <https://doi.org/10.1016/j.quascirev.2020.106300>

679 Chappell, J., 2002. Sea level changes forced ice breakouts in the Last Glacial cycle: New results

680 from coral terraces. *Quat. Sci. Rev.* 21, 1229–1240. [https://doi.org/10.1016/S0277-](https://doi.org/10.1016/S0277-3791(01)00141-X)

681 [3791\(01\)00141-X](https://doi.org/10.1016/S0277-3791(01)00141-X)

682 Chen, S., Huang, Y., Zou, J., Shi, Y., 2013. Mean residence time of global topsoil organic carbon

683 depends on temperature, precipitation and soil nitrogen. *Glob. Planet. Change* 100, 99–108.

684 <https://doi.org/10.1016/j.gloplacha.2012.10.006>

685 Chichagova, O.A., Cherkinsky, A.E., 1993. Problems in radiocarbon dating of soils. *Radiocarbon* 35,

686 351–362. <https://doi.org/10.1017/S0033822200060355>

687 Choi, K., 2005. Pedogenesis of late Quaternary deposits, northern Kyonggi Bay, Korea: Implications

688 for relative sea-level change and regional stratigraphic correlation. *Palaeogeogr.*

689 *Palaeoclimatol. Palaeoecol.* 220, 387–404. <https://doi.org/10.1016/j.palaeo.2005.02.006>

690 Clark, P.U., Huybers, P., 2009. Global change: Interglacial and future sea level. *Nature* 462, 856–

691 857. <https://doi.org/10.1038/462856a>

692 Cleveland, D.M., Atchley, S.C., Nordt, L.C., 2007. Continental sequence stratigraphy of the Upper
 693 Triassic (Norian-Rhaetian) chinle strata, northern New Mexico, U.S.A.: Allocyclic and
 694 autocyclic origins of paleosol-bearing alluvial successions. *J. Sediment. Res.* 77, 909–924.
 695 <https://doi.org/10.2110/jsr.2007.082>

696 Cohen, K.M., Gouw, M.J.P., Holten, J.P., 2003. Fluvio-deltaic floodbasin deposits recording
 697 differential subsidence within a coastal prism (central Rhine-Meuse delta, the Netherlands).
 698 *Ned. Geogr. Stud.* 40–68. <https://doi.org/10.1002/9781444304350.ch17>

699 Cremaschi, M., 1987. Paleosols and Vetusols in the Central Po Plain (Northern Italy): a study in
 700 Quaternary geology and soil development, Unicopli. ed. *Paleosols and Vetusols in the Central*
 701 *Po Plain (Northern Italy): A Study in Quaternary Geology and Soil Development.*, Milano.

702 Cremaschi, M., Nicosia, C., 2012. Sub-Boreal aggradation along the Apennine margin of the Central
 703 Po Plain: geomorphological and geoarchaeological aspects. *Géomorphologie Reli. Process.*
 704 *Environ.* 18, 155–174.

705 Demko, T.M., Currie, B.S., Nicoll, K.A., 2004. Regional paleoclimatic and stratigraphic implications
 706 of paleosols and fluvial/overbank architecture in the Morrison Formation (Upper Jurassic),
 707 Western Interior, USA. *Sediment. Geol.* 167, 115–135.
 708 <https://doi.org/10.1016/j.sedgeo.2004.01.003>

709 Diessel, C.F.K., 1992. Coal facies and depositional environment, in: *Coal-Bearing Depositional*
 710 *Systems.* Springer, pp. 161–264.

711 Dubiel, R.F., Hasiotis, S.T., 2011. Deposystems, paleosols, and climatic variability in a continental
 712 system: the Upper Triassic Chinle Formation, Colorado Plateau, USA. *From River to Rock Rec.*
 713 *Preserv. Fluv. Sediments their Subseq. Interpret. SEPM (Society Sediment. Geol. Spec. Publ.*
 714 *97,* 393–421.

715 Fantoni, R., Bersezio, R., Forcella, F., 2004. Alpine structure and deformation chronology at the

716 Southern Alps-Po Plain border in Lombardy. *Boll. della Soc. Geol. Ital.* 123, 463–476.

717 Feng, Y., 2009. Fundamental considerations of soil organic carbon dynamics: a new theoretical
718 framework. *Soil Sci.* 174, 467–481.

719 Fletcher, W.J., Sánchez Goñi, M.F., Allen, J.R.M., Cheddadi, R., Combourieu-Nebout, N., Huntley,
720 B., Lawson, I., Londeix, L., Magri, D., Margari, V., Müller, U.C., Naughton, F., Novenko, E.,
721 Roucoux, K., Tzedakis, P.C., 2010. Millennial-scale variability during the last glacial in
722 vegetation records from Europe. *Quat. Sci. Rev.* 29, 2839–2864.
723 <https://doi.org/10.1016/j.quascirev.2009.11.015>

724 Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., Rumpel, C., 2007. Stability of organic carbon
725 in deep soil layers controlled by fresh carbon supply. *Nature* 450, 277–280.
726 <https://doi.org/10.1038/nature06275>

727 Fontana, A., Mozzi, P., Marchetti, M., 2014. Alluvial fans and megafans along the southern side of
728 the Alps. *Sediment. Geol.* 301, 150–171. <https://doi.org/10.1016/j.sedgeo.2013.09.003>

729 Garzanti, E., Vezzoli, G., Andò, S., 2011. Paleogeographic and paleodrainage changes during
730 Pleistocene glaciations (Po Plain, Northern Italy). *Earth-Science Rev.* 105, 25–48.
731 <https://doi.org/10.1016/j.earscirev.2010.11.004>

732 Gaudinski, J., Trumbore, S., Davidson, E., 2000. Soil carbon cycling in a temperate forest:
733 radiocarbon-based estimates of residence times, *Biogeochemistry* 51, 33–69.

734 Geyh, M.A., Roeschmann, G., Wijmstra, T.A., Middelorp, A.A., 1983. The Unreliability of 14 C
735 Dates Obtained from Buried Sandy Podzols . *Radiocarbon* 25, 409–416.
736 <https://doi.org/10.1017/s0033822200005695>

737 Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M., 2013. Late Miocene-Middle Pleistocene
738 sequences in the Po Plain - Northern Adriatic Sea (Italy): The stratigraphic record of
739 modification phases affecting a complex foreland basin. *Mar. Pet. Geol.* 42, 50–81.

740 <https://doi.org/10.1016/j.marpetgeo.2012.11.007>

741 Gibling, M.R., Bird, D.J., 1994. Late Carboniferous cyclothems and alluvial paleovalleys in the
742 Sydney Basin, Nova Scotia. *Geol. Soc. Am. Bull.* 106, 105–117. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1994)106<0105:LCCAAP>2.3.CO;2)
743 [7606\(1994\)106<0105:LCCAAP>2.3.CO;2](https://doi.org/10.1130/0016-7606(1994)106<0105:LCCAAP>2.3.CO;2)

744 Gibling, M.R., Fielding, C.R., Sinha, R., Davidson, S.K., Leleu, S., North, C.P., 2011. Alluvial valleys
745 and alluvial sequences: towards a geomorphic assessment. *From River to Rock Rec. Preserv.*
746 *Fluv. Sediments Their Subseq. Interpret. SEPM, Spec. Publ.* 97, 423–447.

747 Gile, L.H., Hawley, J.W., Grossman, R.B., 1981. Soils and geomorphology in the Basin and Range
748 area of southern New Mexico: Guidebook to the Desert Project, New Mexico, Bureau of
749 Mines and Mineral Resources Memoir.

750 Gilet-Blein, N., Marien, G., Evin, J., 1980. of and of of and. *Radiocarbon* 22, 919–929.

751 Gunderson, K.L., Pazzaglia, F.J., Picotti, V., Anastasio, D.A., Kodama, K.P., Rittenour, T., Frankel,
752 K.F., Ponza, A., Berti, C., Negri, A., Sabbatini, A., 2014. Unraveling tectonic and climatic
753 controls on synorogenic growth strata (Northern Apennines, Italy). *Bull. Geol. Soc. Am.* 126,
754 532–552. <https://doi.org/10.1130/B30902.1>

755 Hajek, E.A., Wolinsky, M.A., 2012. Simplified process modeling of river avulsion and alluvial
756 architecture: Connecting models and field data. *Sediment. Geol.* 257–260, 1–30.
757 <https://doi.org/10.1016/j.sedgeo.2011.09.005>

758 Helmens, K.F., 2014. The last interglacial-glacial cycle (MIS 5-2) re-examined based on long proxy
759 records from central and northern europe. *Quat. Sci. Rev.* 86, 115–143.
760 <https://doi.org/10.1016/j.quascirev.2013.12.012>

761 Hijma, M.P., Cohen, K.M., 2011. Holocene transgression of the Rhine river mouth area, The
762 Netherlands/Southern North Sea: Palaeogeography and sequence stratigraphy.
763 *Sedimentology* 58, 1453–1485. <https://doi.org/10.1111/j.1365-3091.2010.01222.x>

764 Hofmann, F., Reichenbacher, B., Farley, K.A., 2017. Evidence for >5 Ma paleo-exposure of an
 765 Eocene–Miocene paleosol of the Bohnert Formation, Switzerland. *Earth Planet. Sci. Lett.* 465,
 766 168–175. <https://doi.org/10.1016/j.epsl.2017.02.042>

767 Holbrook, J., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic
 768 deformation: A brief review and critique of a tool for recognizing subtle epeirogenic
 769 deformation in modern and ancient settings. *Tectonophysics* 305, 287–306.
 770 [https://doi.org/10.1016/S0040-1951\(99\)00011-6](https://doi.org/10.1016/S0040-1951(99)00011-6)

771 Hošek, J., Lisá, L., Hambach, U., Petr, L., Vejrostová, L., Bajer, A., Grygar, T.M., Moska, P., Gottvald,
 772 Z., Horsák, M., 2017. Middle Pleniglacial pedogenesis on the northwestern edge of the
 773 Carpathian basin: A multidisciplinary investigation of the Bíňa pedo-sedimentary section, SW
 774 Slovakia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 487, 321–339.
 775 <https://doi.org/10.1016/j.palaeo.2017.09.017>

776 Ishii, Y., Hori, K., Momohara, A., Nakanishi, T., Hong, W., 2016. Middle to late-Holocene decreased
 777 fluvial aggradation and widespread peat initiation in the Ishikari lowland (northern Japan).
 778 *The Holocene* 26, 1924–1938.

779 Janssens, M.M., Kasse, C., Bohncke, S.J.P., Greaves, H., Cohen, K.M., Wallinga, J., Hoek, W.Z., 2012.
 780 Climate-driven fluvial development and valley abandonment at the last glacial-interglacial
 781 transition (Oude IJssel-Rhine, Germany). *Geol. en Mijnbouw/Netherlands J. Geosci.* 91, 37–
 782 62. <https://doi.org/10.1017/s001677460000055x>

783 Kaiser, K., Hilgers, A., Schlaak, N., Jankowski, M., Kühn, P., Bussemer, S., Przegliska, K., 2009.
 784 Palaeopedological marker horizons in northern central Europe: Characteristics of Lateglacial
 785 Usselo and Finow soils. *Boreas* 38, 591–609. [https://doi.org/10.1111/j.1502-](https://doi.org/10.1111/j.1502-3885.2008.00076.x)
 786 [3885.2008.00076.x](https://doi.org/10.1111/j.1502-3885.2008.00076.x)

787 Kalisz, B., Lachacz, A., Glazewski, R., 2010. Transformation of some organic matter components in

788 organic soils exposed to drainage. Turkish J. Agric. For. 34, 245–256.

789 <https://doi.org/10.3906/tar-0905-33>

790 Kleber, M., 2010. What is recalcitrant soil organic matter? Environ. Chem. 7, 320–332.

791 <https://doi.org/10.1071/EN10006>

792 Kusters, E.C., Suter, J.R., 1993. Facies relationships and systems tracts in the late Holocene

793 Mississippi Delta Plain. J. Sediment. Petrol. 63, 727–733. [https://doi.org/10.1306/D4267BCC-](https://doi.org/10.1306/D4267BCC-2B26-11D7-8648000102C1865D)

794 [2B26-11D7-8648000102C1865D](https://doi.org/10.1306/D4267BCC-2B26-11D7-8648000102C1865D)

795 Kraus, M.J., 1999. Paleosols in clastic sedimentary rocks: Their geologic applications. Earth Sci. Rev.

796 47, 41–70. [https://doi.org/10.1016/S0012-8252\(99\)00026-4](https://doi.org/10.1016/S0012-8252(99)00026-4)

797 Kraus, M.J., Bown, T.M., 1993. Palaeosols and sandbody prediction in alluvial sequences. Geol.

798 Soc. London, Spec. Publ. 73, 23–31.

799 Kvale, E.P., Archer, A.W., 2007. Paleovalley fills: Trunk vs. tributary. Am. Assoc. Pet. Geol. Bull. 91,

800 809–821. <https://doi.org/10.1306/11060606022>

801 Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G., Scicchitano, G., Silenzi, S., 2011. Sea

802 level change along the Italian coast during the Holocene and projections for the future. Quat.

803 Int. 232, 250–257. <https://doi.org/10.1016/j.quaint.2010.04.026>

804 Larionova, A.A., Maltseva, A.N., Lopes de Gerenyu, V.O., Kvitkina, A.K., Bykhovets, S.S., Zolotareva,

805 B.N., Kudeyarov, V.N., 2017. Effect of temperature and moisture on the mineralization and

806 humification of leaf litter in a model incubation experiment. Eurasian Soil Sci. 50, 422–431.

807 <https://doi.org/10.1134/S1064229317020089>

808 Lewis, S.G., Maddy, D., Scaife, R.G., 2001. The fluvial system response to abrupt climate change

809 during the last cold stage: The Upper Pleistocene River Thames fluvial succession at Ashton

810 Keynes, UK. Glob. Planet. Change 28, 341–359. [https://doi.org/10.1016/S0921-](https://doi.org/10.1016/S0921-8181(00)00083-7)

811 [8181\(00\)00083-7](https://doi.org/10.1016/S0921-8181(00)00083-7)

812 Machette, M.N., 1985. Calcific soils of the southwestern United States. *Soils Quat. Geol.*
813 Southwest. United States Geol. Soc. Am. Spec. Pap. 203, 1–21.

814 Maestrelli, D., Benvenuti, M., Bonini, M., Carnicelli, S., Piccardi, L., Sani, F., 2018. The structural
815 hinge of a chain-foreland basin: Quaternary activity of the Pede-Apennine Thrust front
816 (Northern Italy). *Tectonophysics* 723, 117–135. <https://doi.org/10.1016/j.tecto.2017.12.006>

817 Magri, D., 1999. Late Quaternary vegetation history at Lagaccione near Lago di Bolsena (central
818 Italy). *Rev. Palaeobot. Palynol.* 106, 171–208. [https://doi.org/10.1016/S0034-6667\(99\)00006-](https://doi.org/10.1016/S0034-6667(99)00006-8)
819 8

820 Marabini, S., Vai G.B., 2020. *Carta Geologica della Pianura tra Imola e Ravenna*, Thèodolite Editore,
821 Imola, 81pp. (in Italian).

822 Martin, C.W., Johnson, W.C., 1995. Variation in radiocarbon ages of soil organic matter fractions
823 from late Quaternary buried soils. *Quat. Res.* 43, 232–237.

824 Matthews, J.A., 1980. Some Problems and Implications of ¹⁴C Dates from a Podzol Buried beneath
825 an End Moraine at Haugabreen , Southern Norway Author (s): John A . Matthews Published
826 by : Taylor & Francis , Ltd . on behalf of the Swedish Society for Anthropology and Geography
827 62, 185–208.

828 Matthews, J.A., 1981. Natural ¹⁴C age/depth gradient in a buried soil. *Naturwissenschaften* 68,
829 472–474.

830 Matthews, J.A., Dresser, P.Q., 1983. Intensive ¹⁴C dating of a buried palaeosol horizon. *Geol.*
831 *Föreningen i Stock. Förhandlingar* 105, 59–63.

832 McCarthy, P.J., Plint, A.G., 1998. Recognition of interfluvial sequence boundaries: integrating
833 paleopedology and sequence stratigraphy. *Geology* 26, 387–390.
834 [https://doi.org/10.1130/0091-7613\(1998\)026<0387:ROISBI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1998)026<0387:ROISBI>2.3.CO;2)

835 McCarthy, P.J., Plint, A.G., 2003. Spatial variability of palaeosols across Cretaceous interfluvial in

836 the Dunvegan Formation, NE British Columbia, Canada: Palaeohydrological,
837 palaeogeomorphological and stratigraphic implications. *Sedimentology* 50, 1187–1220.
838 <https://doi.org/10.1111/j.1365-3091.2003.00600.x>

839 Meingast, K.M., Grunert, B.K., Green, S.A., Kane, E.S., Khademimoshgenani, N., 2020. Insights on
840 dissolved organic matter production revealed by removal of charge-transfer interactions in
841 senescent leaf leachates. *Water (Switzerland)* 12. <https://doi.org/10.3390/W12092356>

842 Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial
843 deposits. *Earth-Science Rev.* 22, 261–308.

844 Moine, O., Antoine, P., Hatté, C., Landais, A., Mathieu, J., Prud'homme, C., Rousseau, D.D., 2017.
845 The impact of Last Glacial climate variability in west-European loess revealed by radiocarbon
846 dating of fossil earthworm granules. *Proc. Natl. Acad. Sci. U. S. A.* 114, 6209–6214.
847 <https://doi.org/10.1073/pnas.1614751114>

848 Mol, J., 1997. Fluvial response to Weichselian climate changes in the Niederlausitz (Germany). *J.*
849 *Quat. Sci.* 12, 43–60. [https://doi.org/10.1002/\(SICI\)1099-1417\(199701/02\)12:1<43::AID-](https://doi.org/10.1002/(SICI)1099-1417(199701/02)12:1<43::AID-JQS291>3.0.CO;2-0)
850 [JQS291>3.0.CO;2-0](https://doi.org/10.1002/(SICI)1099-1417(199701/02)12:1<43::AID-JQS291>3.0.CO;2-0)

851 Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., Piccin, A., 2017. The Alpine LGM in the boreal ice-
852 sheets game. *Sci. Rep.* 7, 1–8. <https://doi.org/10.1038/s41598-017-02148-7>

853 Morelli, A., Bruno, L., Cleveland, D.M., Drexler, T.M., Amorosi, A., 2017. Reconstructing Last Glacial
854 Maximum and Younger Dryas paleolandscapes through subsurface paleosol stratigraphy: An
855 example from the Po coastal plain, Italy. *Geomorphology* 295, 790–800.
856 <https://doi.org/10.1016/j.geomorph.2017.08.013>

857 Mozzi, P., Bini, C., Zilocchi, L., Becattini, R., Lippi, M.M., 2003. Stratigraphy, palaeopedology and
858 palynology of late Pleistocene and Holocene deposits in the landward sector of the Lagoon of
859 Venice (Italy), in relation to the Caranto level. *Alp. Mediterr. Quat.* 16, 193–210.

860 Muttoni, G., Carcano, C., Garzanti, E., Ghielmi, M., Piccin, A., Pini, R., Rogledi, S., Sciunnach, D.,
861 2003. Onset of major Pleistocene glaciations in the Alps. *Geology* 31, 989–992.
862 <https://doi.org/10.1130/G19445.1>

863 Muttoni, G., Scardia, G., Kent, D. V., Morsiani, E., Tremolada, F., Cremaschi, M., Peretto, C., 2011.
864 First dated human occupation of Italy at ~0.85Ma during the late Early Pleistocene climate
865 transition. *Earth Planet. Sci. Lett.* 307, 241–252. <https://doi.org/10.1016/j.epsl.2011.05.025>

866 Orlova, L.A., Panychev, V.A., 1993. The reliability of radiocarbon dating buried soils. *Radiocarbon*
867 35, 369–377. <https://doi.org/10.1017/S0033822200060379>

868 Pandey, D., Agrawal, M., Singh Bohra, J., Adhya, T.K., Bhattacharyya, P., 2014. Recalcitrant and
869 labile carbon pools in a sub-humid tropical soil under different tillage combinations: A case
870 study of rice-wheat system. *Soil Tillage Res.* 143, 116–122.
871 <https://doi.org/10.1016/j.still.2014.06.001>

872 Pati, P., Verma, A.K., Dash, C., Patel, N.K., Gupta, A., Sharma, V., Jakhmola, R.P., Parkash, B.,
873 Awasthi, A.K., Saraf, A.K., 2019. Influence of neotectonism on geomorphology and
874 depositional architecture of the Gandak megafan, middle Ganga plain, India. *Geomorphology*
875 327, 489–503. <https://doi.org/10.1016/j.geomorph.2018.11.029>

876 Pellegrini, C., Asioli, A., Bohacs, K.M., Drexler, T.M., Feldman, H.R., Sweet, M.L., Maselli, V., Rovere,
877 M., Gamberi, F., Valle, G.D., Trincardi, F., 2018. The late Pleistocene Po River lowstand wedge
878 in the Adriatic Sea: Controls on architecture variability and sediment partitioning. *Mar. Pet.*
879 *Geol.* 96, 16–50. <https://doi.org/10.1016/j.marpetgeo.2018.03.002>

880 Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration
881 from an extended Barbados sea level record. *Quat. Sci. Rev.* 25, 3322–3337.
882 <https://doi.org/10.1016/j.quascirev.2006.04.010>

883 Phillips, J.D., 2011. Universal and local controls of avulsions in southeast Texas Rivers.

884 Geomorphology 130, 17–28. <https://doi.org/10.1016/j.geomorph.2010.10.001>

885 Picotti, V., Pazzaglia, F.J., 2008. A new active tectonic model for the construction of the Northern
886 Apennines mountain front near Bologna (Italy). *J. Geophys. Res. Solid Earth* 113, 1–24.
887 <https://doi.org/10.1029/2007JB005307>

888 Pini, R., Ravazzi, C., Reimer, P.J., 2010. The vegetation and climate history of the last glacial cycle in
889 a new pollen record from Lake Fimon (southern Alpine foreland, N-Italy). *Quat. Sci. Rev.* 29,
890 3115–3137. <https://doi.org/10.1016/j.quascirev.2010.06.040>

891 Piovan, S., Mozzi, P., Zecchin, M., 2012. The interplay between adjacent Adige and Po alluvial
892 systems and deltas in the late Holocene (Northern Italy). *Géomorphologie Reli. Process.*
893 *Environ.* 18, 427–440.

894 Plint, A.G., Moore, J., Plint, A., Sanders, J., Ulic, D., 2001. stratigraphy : Updip expression Formation
895 , Alberta foreland. October 11, 1967–2001.

896 Rasbury, E.T., Hanson, G.N., Meyers, W.J., Saller, A.H., 1997. Dating of the time of sedimentation
897 using U-Pb ages for paleosol calcite. *Geochim. Cosmochim. Acta* 61, 1525–1529.
898 [https://doi.org/10.1016/S0016-7037\(97\)00043-4](https://doi.org/10.1016/S0016-7037(97)00043-4)

899 Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I.,
900 Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W.Z., Lowe, J.J.,
901 Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallenga, P., Vinther,
902 B.M., Walker, M.J.C., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt
903 climatic changes during the Last Glacial period based on three synchronized Greenland ice-
904 core records: Refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* 106,
905 14–28. <https://doi.org/10.1016/j.quascirev.2014.09.007>

906 Ravazzi, C., Donegana, M., Vescovi, E., Arpentini, E., Caccianiga, M., Kaltenrieder, P., Londeix, L.,
907 Marabini, S., Mariani, S., Pini, R., Vai, G.B., Wick, L., 2006. A new Late-glacial site with *Picea*

abies in the northern Apennine foothills: An exception to the model of glacial refugia of trees.
 Veg. Hist. Archaeobot. 15, 357–371. <https://doi.org/10.1007/s00334-006-0055-9>
 Ravazzi, C., Deaddis, M., De Amicis, M., Marchetti, M., Vezzoli, G., Zanchi, A., 2012. Évolution de la
 plaine centrale du Pô entre les rivières Adda et Serio au cours des 40 derniers millénaires.
 Geomorphol. Reli. Process. Environ. 131–154. <https://doi.org/10.4000/geomorphologie.9794>
 Regione Emilia-Romagna & Eni-Agip, 1998. Riserve idriche sotterranee della Regione Emilia-
 Romagna. S.EL.CA, Firenze (*in Italian*).
 Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M.,
 Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J.,
 Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C.,
 Van Der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M.,
 Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich,
 R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo,
 S., 2020. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal
 kBP). Radiocarbon 62, 725–757. <https://doi.org/10.1017/RDC.2020.41>
 Richardson, J.L., Vepraskas, M.J., 2001. Wetland soilsgenesis, hydrology, landscapes, and
 classification.
 Rousseau, D.D., Sima, A., Antoine, P., Hatté, C., Lang, A., Zöller, L., 2007. Link between European
 and North Atlantic abrupt climate changes over the last glaciation. Geophys. Res. Lett. 34, 2–
 7. <https://doi.org/10.1029/2007GL031716>
 Rousseau, D.D., Antoine, P., Gerasimenko, N., Sima, A., Fuchs, M., Hatté, C., Moine, O., Zoeller, L.,
 2011. North Atlantic abrupt climatic events of the last glacial period recorded in Ukrainian
 loess deposits. Clim. Past 7, 221–234. <https://doi.org/10.5194/cp-7-221-2011>
 Scharpenseel, H.W., 1971. Radiocarbon dating of soils--problems, troubles, hopes. Paleopedol.

932 Orig. Nat. Dating Paleosols. Pap. 77–88.

933 Shanley, K.W., McCabe, P.J., 1994. Perspectives on the sequence stratigraphy of continental strata.

934 Am. Assoc. Pet. Geol. Bull. 78, 544–568. [https://doi.org/10.1306/bdff9258-1718-11d7-](https://doi.org/10.1306/bdff9258-1718-11d7-8645000102c1865d)

935 8645000102c1865d

936 Synal, H.A., Stocker, M., and Suter, M., 2007. MICADAS: A new compact radiocarbon AMS system.

937 Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with

938 Materials and Atoms 259, 7-13. <https://doi.org/10.1016/j.nimb.2007.01.138>

939 Soares, M.V.T., Basilici, G., Lorenzoni, P., Colombero, L., Mountney, N.P., Martinelli, A.G., Ferreira

940 Mesquita, Á., da Silva Marinho, T., Vásconez García, R.G., Marconato, A., 2020. Landscape

941 and depositional controls on palaeosols of a distributive fluvial system (Upper Cretaceous,

942 Brazil). Sediment. Geol. 410, 105774. <https://doi.org/10.1016/j.sedgeo.2020.105774>

943 Soldati, M., Borgatti, L., Cavallin, A., De Amicis, M., Frigerio, S., Giardino, M., Mortara, G.,

944 Pellegrini, G.B., Ravazzi, C., Surian, N., Tellini, C., Zanchi, A., Alberto, W., Albanese, D., Chelli,

945 A., Corsini, A., Marchetti, M., Palomba, M., Panizza, M., 2006. Geomorphological evolution of

946 slopes and climate changes in Northern Italy during the late quaternary: Spatial and temporal

947 distribution of landslides and landscape sensitivity implications. Geogr. Fis. e Din. Quat. 29,

948 164–183.

949 Stolt, M.H., Rabenhorst, M.C., 2011. Introduction and historical development of subaqueous soil

950 concepts. 36: 1-14.

951 Storms, J.E.A., Weltje, G.J., Terra, G.J., Cattaneo, A., Trincardi, F., 2008. Coastal dynamics under

952 conditions of rapid sea-level rise: Late Pleistocene to Early Holocene evolution of barrier-

953 lagoon systems on the northern Adriatic shelf (Italy). Quat. Sci. Rev. 27, 1107–1123.

954 <https://doi.org/10.1016/j.quascirev.2008.02.009>

955 Stouthamer, E., Cohen, K.M., Gouw, M.J.P., 2011. Avulsion and its implications for fluvial-deltaic

956 architecture: insights from the Holocene Rhine-Meuse delta. SEPM Spec. Publ. 97, 215–232.
 957 Synal HA, Stocker M, and Suter M. 2007. MICADAS: A new compact radiocarbon AMS system.
 958 *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with*
 959 *Materials and Atoms* 259: 7-13.
 960 Tebbens, L.A., Veldkamp, A., Westerhoff, W., Kroonenberg, S.B., 1999. Fluvial incision and channel
 961 downcutting as a response to Late-glacial and Early Holocene climate change: The lower
 962 reach of the river Meuse (Maas), The Netherlands. J. Quat. Sci. 14, 59–75.
 963 [https://doi.org/10.1002/\(SICI\)1099-1417\(199902\)14:1<59::AID-JQS408>3.0.CO;2-Z](https://doi.org/10.1002/(SICI)1099-1417(199902)14:1<59::AID-JQS408>3.0.CO;2-Z)
 964 Toonen, W.H.J., Kleinhans, M.G., Cohen, K.M., 2012. Sedimentary architecture of abandoned
 965 channel fills. Earth Surf. Process. Landforms 37, 459–472. <https://doi.org/10.1002/esp.3189>
 966 Törnqvist, T.E., 1993. HOLOCENE ALTERNATION OF MEANDERING AND ANASTOMOSING
 967 Formation Kreftenheye Formation m below Dutch Ordnance Datum (O . D .) _ Twent ~ e F ~
 968 rmation ~ Betuwe and Formation Broek Formation / T ~ wente Formation. J. Sediment.
 969 Petrol. 63, 683–693.
 970 Trendell, A.M., Atchley, S.C., Nordt, L.C., 2012. Depositional and diagenetic controls on reservoir
 971 attributes within a fluvial outcrop analog: Upper Triassic Sonsela member of the Chinle
 972 Formation, Petrified Forest National Park, Arizona. Am. Assoc. Pet. Geol. Bull. 96, 679–707.
 973 <https://doi.org/10.1306/08101111025>
 974 Tsatskin, A., Sandler, A., Avnaim-Katav, S., 2015. Quaternary subsurface paleosols in Haifa Bay,
 975 Israel: A new perspective on stratigraphic correlations in coastal settings. Palaeogeogr.
 976 Palaeoclimatol. Palaeoecol. 426, 285–296. <https://doi.org/10.1016/j.palaeo.2015.03.018>
 977 van Balen, R.T., Busschers, F.S., Tucker, G.E., 2010. Modeling the response of the Rhine-Meuse
 978 fluvial system to Late Pleistocene climate change. Geomorphology 114, 440–452.
 979 <https://doi.org/10.1016/j.geomorph.2009.08.007>

980 Vandenberghe, J., 2003. Climate forcing of fluvial system development: An evolution of ideas.
 981 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)
 982 Vannoli, P., Burrato, P., Valensise, G., 2015. The Seismotectonics of the Po Plain (Northern Italy):
 983 Tectonic Diversity in a Blind Faulting Domain. Pure Appl. Geophys. 172, 1105–1142.
 984 <https://doi.org/10.1007/s00024-014-0873-0>
 985 Vescovi, E., Ammann, B., Ravazzi, C., Tinner, W., 2010. A new Late-glacial and Holocene record of
 986 vegetation and fire history from Lago del Greppo, northern Apennines, Italy. Veg. Hist.
 987 Archaeobot. 19, 219–233. <https://doi.org/10.1007/s00334-010-0243-5>
 988 Viseras, C., Calvache, M.L., Soria, J.M., Fernández, J., 2003. Differential features of alluvial fans
 989 controlled by tectonics or eustatic accommodation space. Examples from the Betic Cordillera,
 990 Spain. Geomorphology 50, 181–202. [https://doi.org/10.1016/S0169-555X\(02\)00214-3](https://doi.org/10.1016/S0169-555X(02)00214-3)
 991 Wadsworth, J., Boyd, R., Diessel, C., Leckie, D., 2003. Stratigraphic style of coal and non-marine
 992 strata in a high accommodation setting: Falher Member and Gates Formation (Lower
 993 Cretaceous), western Canada. Bull. Can. Pet. Geol. 51, 275–303.
 994 <https://doi.org/10.2113/51.3.275>
 995 Wright, V.P., Marriott, S.B., 1993. The sequence stratigraphy of fluvial depositional systems: the
 996 role of floodplain sediment storage. Sediment. Geol. 86, 203–210.
 997 Zeeden, C., Hambach, U., Veres, D., Fitzsimmons, K., Obreht, I., Böskén, J., Lehmkuhl, F., 2018.
 998 Millennial scale climate oscillations recorded in the Lower Danube loess over the last glacial
 999 period. Palaeogeogr. Palaeoclimatol. Palaeoecol. 509, 164–181.
 1000 <https://doi.org/10.1016/j.palaeo.2016.12.029>
 1001 Zerboni, A., Trombino, L., Frigerio, C., Livio, F., Berlusconi, A., Michetti, A.M., Rodnight, H., Spötl,
 1002 C., 2015. The loess-paleosol sequence at Monte Netto: a record of climate change in the
 1003 Upper Pleistocene of the central Po Plain, northern Italy. J. Soils Sediments 15, 1329–1350.

1004

<https://doi.org/10.1007/s11368-014-0932-2>

1005

Zuffetti, C., Trombino, L., Zembo, I., Bersezio, R., 2018. Soil evolution and origin of landscape in a

1006

late Quaternary tectonically mobile setting: The Po Plain-Northern Apennines border in

1007

Lombardy (Italy). Catena 171, 376–397. <https://doi.org/10.1016/j.catena.2018.07.026>

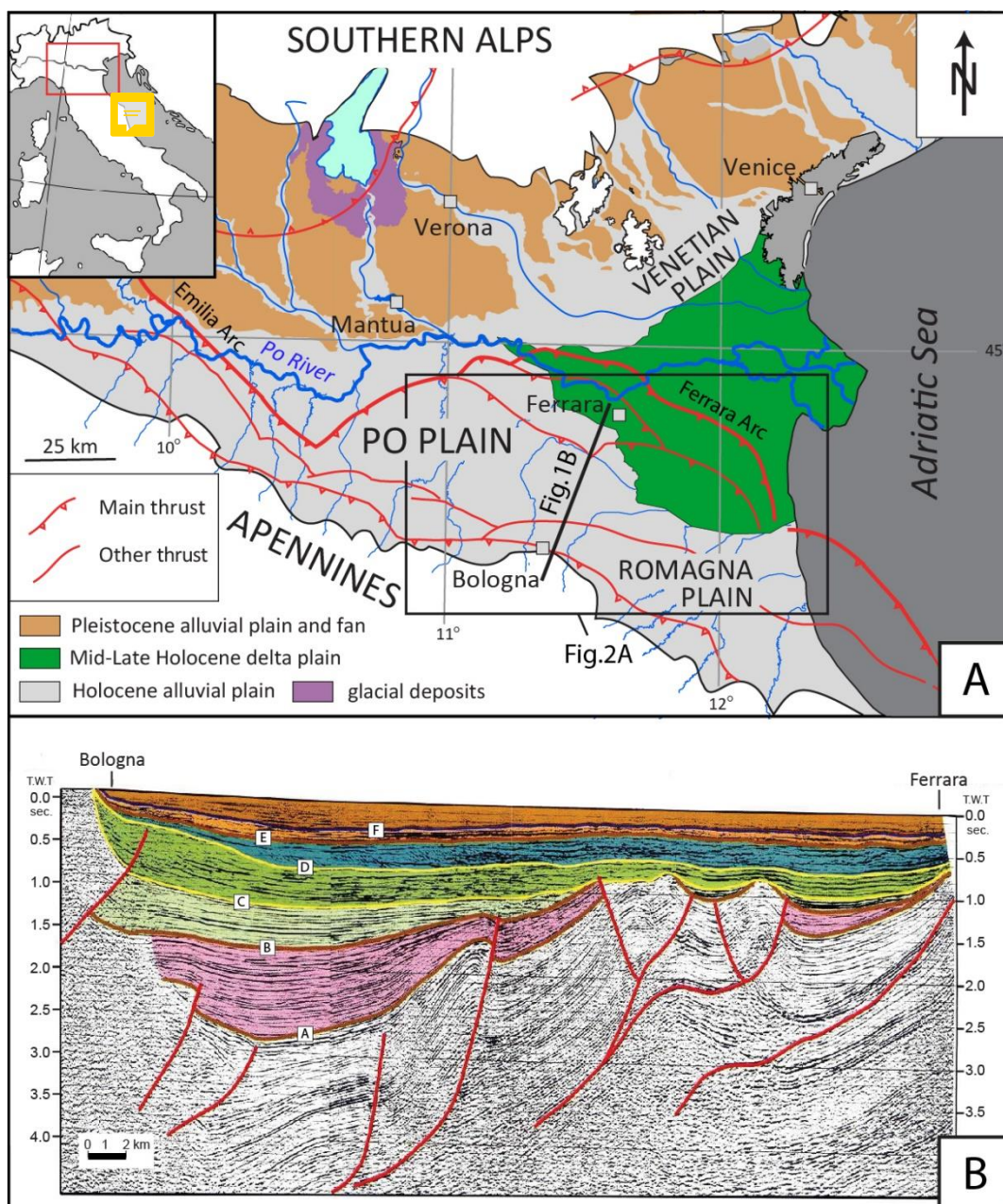
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Figures and captions

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1013 Fig. 1 – A. Geological map of the Po Plain, with location of the study area and of the seismic profile
1014 of Fig. 1B (modified after Bruno et al., 2019). The extent of Pleistocene alluvial deposits is from
1015 Fontana et al. (2014). Buried structures are modified after Burrato et al., (2003). B. Interpreted deep
1016 seismic profile (from Regione Emilia-Romagna & Eni-Agip, 1998, location in Figure 1A), with
1017 identification of the major blind thrusts (red lines) and main stratigraphic unconformities (lines from
1018 A–F) within the Po Basin fill (coloured area).

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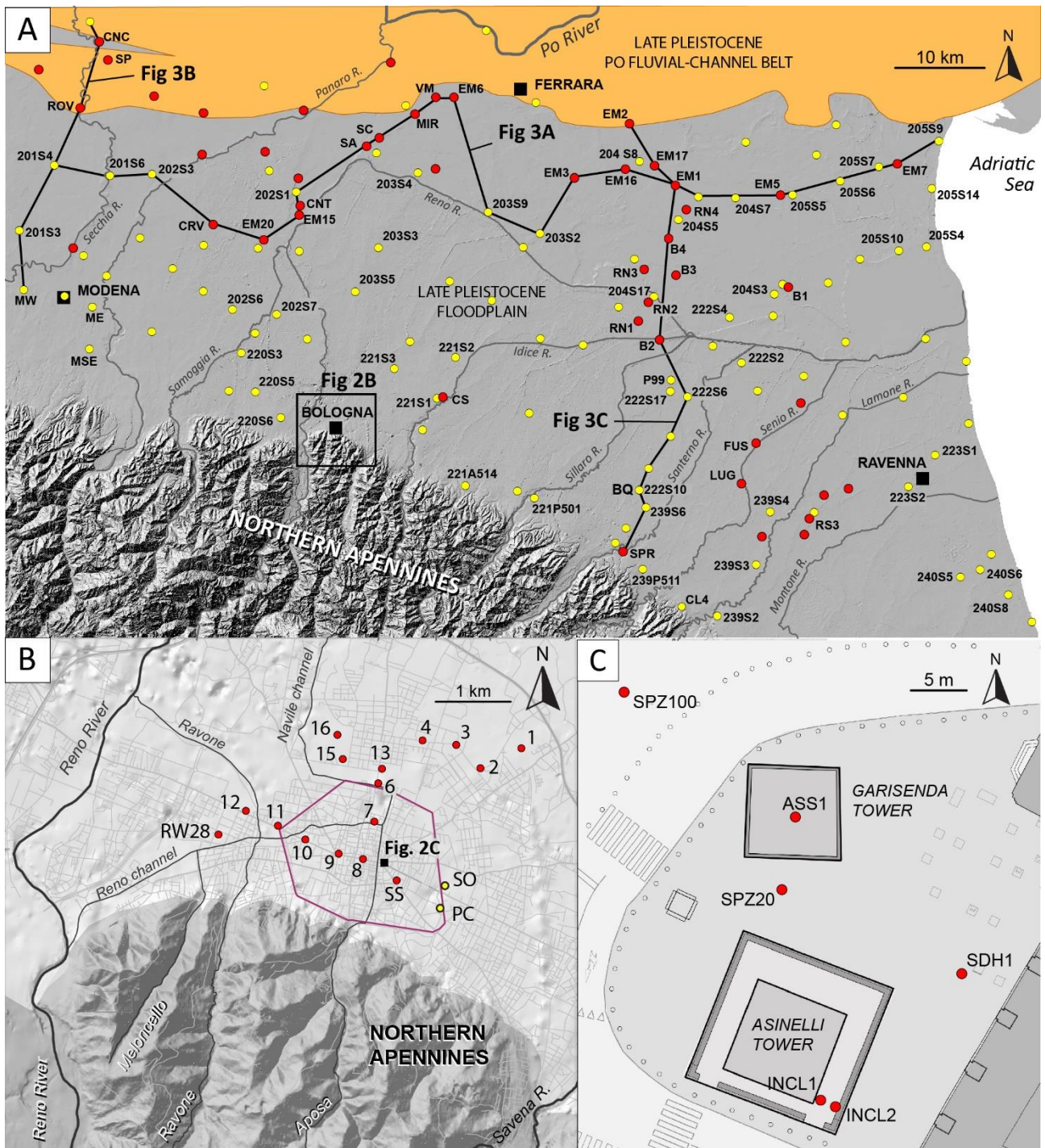
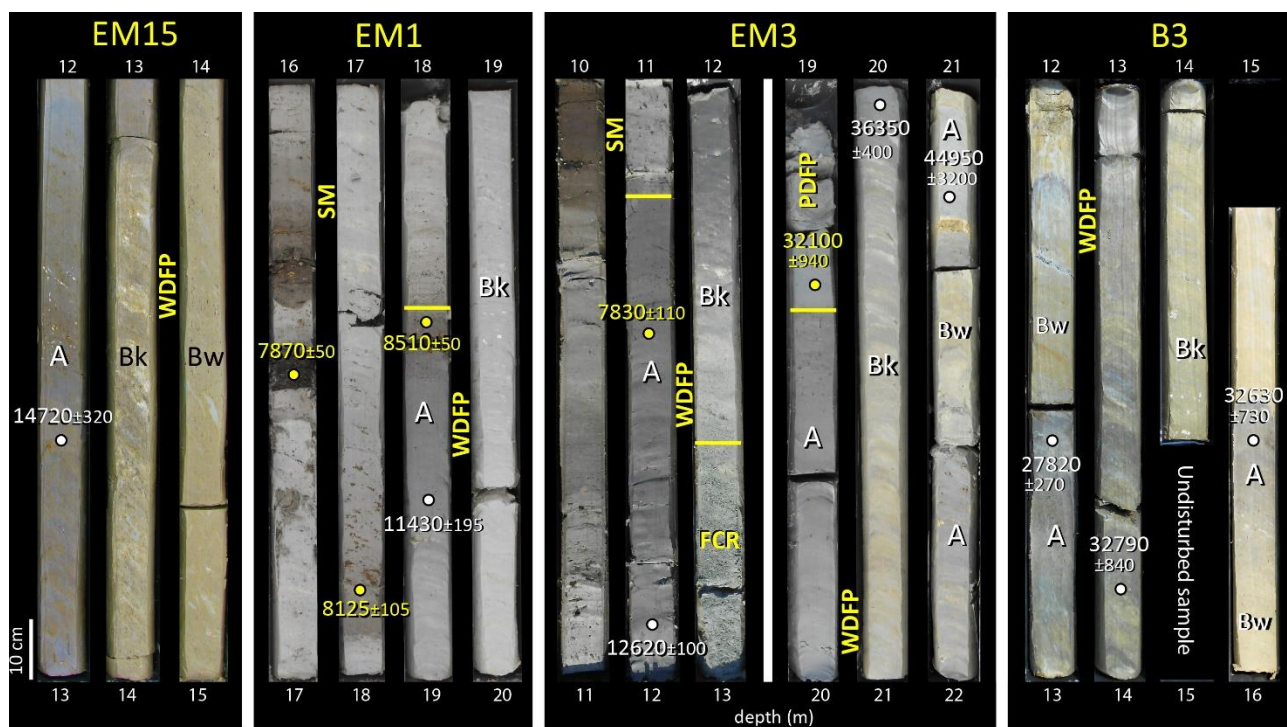


Fig. 2 – A. Study area with location of cores (red circles), core descriptions (yellow circles) and cross-sections of Fig. 5. B. Close-up on the Bologna area, with location of cores shown in Fig. 6. C. Location of cores drilled in the Two-Towers Medieval district (modified after Bruno et al., 2020b).



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Fig. 3 – Representative photographs of paleosols from cores EM1, EM3 and B3 (location in Fig. 2).

WDFP: well-drained floodplain; PDEF: poorly-drained floodplain; SW: swamp; FCR: fluvial-channel-related deposits. For pedological horizons A, Bk and Bw, see text. The white dates (cal kyr B.P.) are from bulk-sediment samples, whereas the yellow ones are from plant macrofossils.

depth (m)			lithology	colour	consistency	accessory material	reaction to HCl	facies association
6	14720 \pm 320			brown (10 YR 4/4)		DOM, RF	weak	WDFP (A horizon)
8	16760 \pm 100	PH	clayey silt	wheat (10 YR 8/4)	hard	CC (3), RF	strong	WDFP (Bk horizon)
10	10340 \pm 120			brown (10 YR 3/3)		DOM, RF	weak	WDFP (A horizon)
12	11880 \pm 120			beige (10 YR 8/2)		CC (1, 2)	strong	WDFP (Bk horizon)
12	13540 \pm 80	PH	clayey silt					
8	5050 \pm 260		H1 silty clay	brown (7.5YR 5/1)	firm	DOM, RF, Eneolithic artifacts	weak	WDFP (A horizon)
8	8210 \pm 160		clayey silt	grey (7.5YR 6/1)		RF	moderate	WDFP (Bw horizon)
10			clayey and sandy silt	with orange mottles				FCR
10			silty clay with silt intercalations	grey (7.5YR 6/1)	weak			PDFP
12	11870 \pm 270	PH		dark grey (10YR 3/1)		DOM, UOM on top	weak	WDFP (A horizon)
14			clayey silt	grey (5Y 7/1)	firm	CC (2), RF	strong	WDFP (Bk horizon)
14	25850 \pm 360	P3		dark grey (5Y 4/1)	hard	DOM, RF	weak	WDFP (A horizon)
				olive grey (5Y 6/1)		CC (2), RF	strong	WDFP (Bk horizon)
17	8870 \pm 90			grey (2.5YR 7/1)	weak	Abundant UOM	weak	SM
19	11660 \pm 160	PH	silty clay	light grey (2.5YR 8/1)		CC (1) sparse UOM	moderate	PDFP
				grey (2.5Y 6/1)		DOM, sparse UOM on top	weak	WDFP (A horizon)
				light grey (2.5YR 8/1)	firm	CC (2), RF	strong	WDFP (Bk horizon)
17	7870 \pm 50			light grey (7.5YR 8/1)	very weak	Abundant UOM, peat, locally DOM	moderate, weak on peat	SM
19	8125 \pm 105		silty clay	grey (2.5Y 6/1)	firm	DOM, sparse UOM on top	weak	WDFP (A horizon)
19	8510 \pm 50			light grey (2.5YR 8/1)	hard	CC (2)	strong	WDFP (Bk horizon)
19	11430 \pm 195	PH						
8	7210 \pm 30			light grey (clay, 5YR 8/1)	very weak	UOM, peat at the base	moderate, weak on peat	SM
8	7380 \pm 40			brown (peat, 2.5Y 3/2)	weak	sparse UOM		SM (O horizon)
10	7630 \pm 20			dark grey (5Y 4/1)	firm	DOM	weak	PDFP
10	7960 \pm 40							WDFP (A horizon)
10	10000 \pm 120	PH	silty clay					WDFP (Bw horizon)
12			silty clay- sandy silt	grey (10R 7/1) with orange (10 YR 8/6) mottles		RF	moderate	FCR
12			silty clay, clayey silt		firm			WDFP (Bw horizon)
14	27820 \pm 130			dark grey (7.5Y 5/1)	hard	DOM, RF	weak	WDFP (A horizon)
14	32790 \pm 440	P3	silty clay	beige-brown (10YR 6/3)		CC (2,3), RF	strong	WDFP (Bk horizon)
				beige (7.5Y 8/2)	firm	RF		WDFP (Bw horizon)
	32630 \pm 370	P2		dark grey (10YR 5/1)		DOM, RF	weak	WDFP (A horizon)

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1032 Fig. 4 – Sedimentological characters and radiocarbon ages of paleosols P2, P3, PH and H1 from cores
1033 RW28, 16, 17, EM1, EM20 and B3 (for location see Fig. 2). DOM: dissolved organic matter; UOM:
1034 undecomposed organic matter; RF: redoximorphic features; CC carbonate concretions (the number
1035 indicates the evolutionary stage, from Gile et al., 1981; Machette et al., 1985). WDFP: well-drained

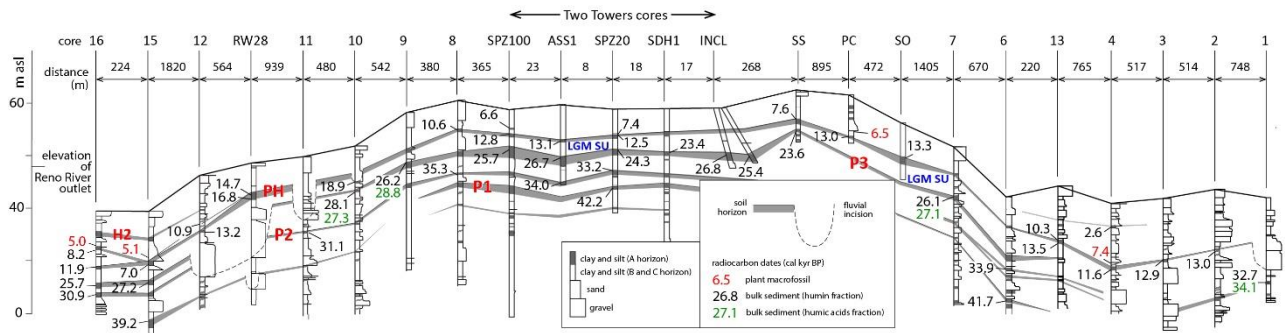
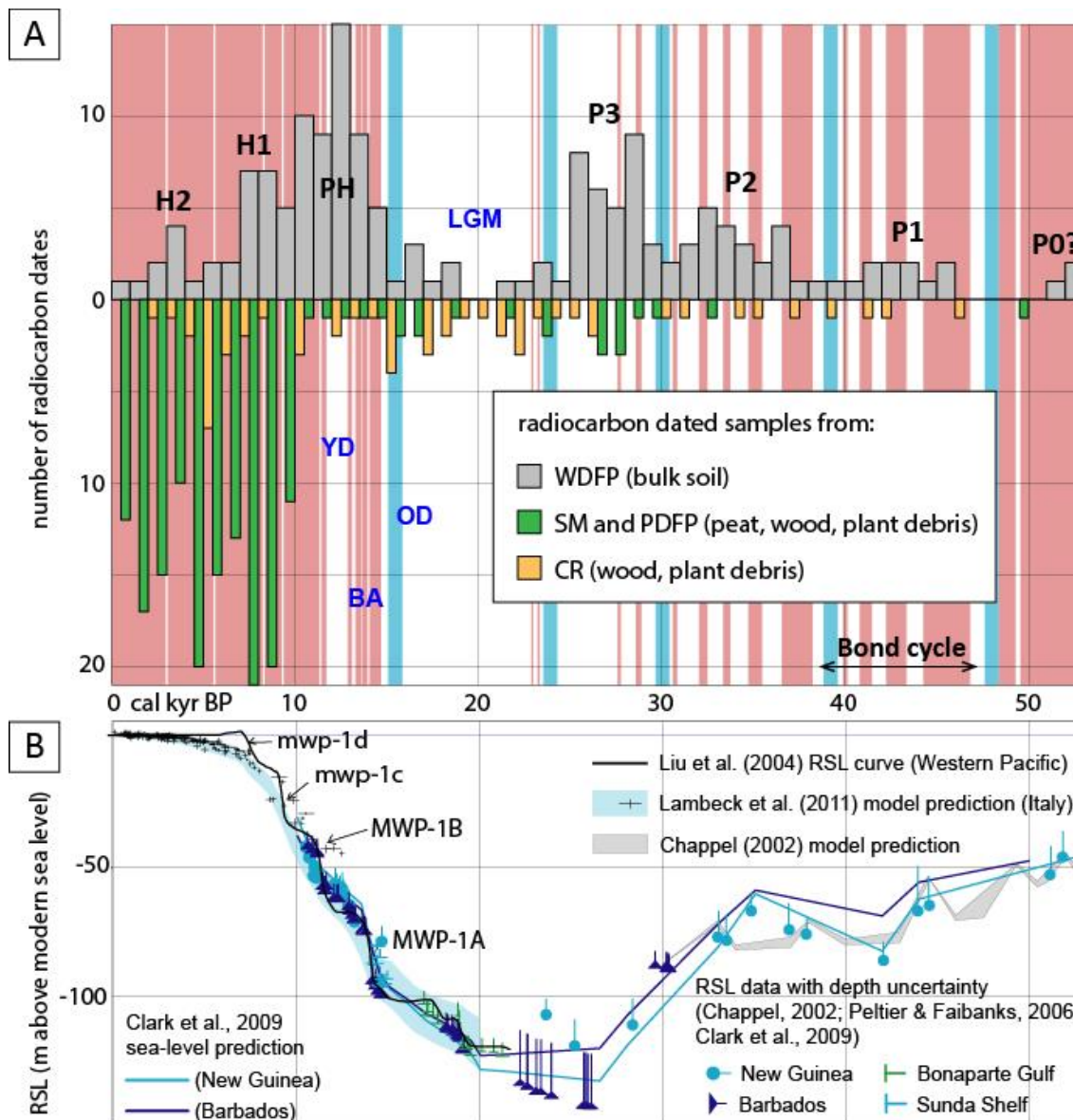
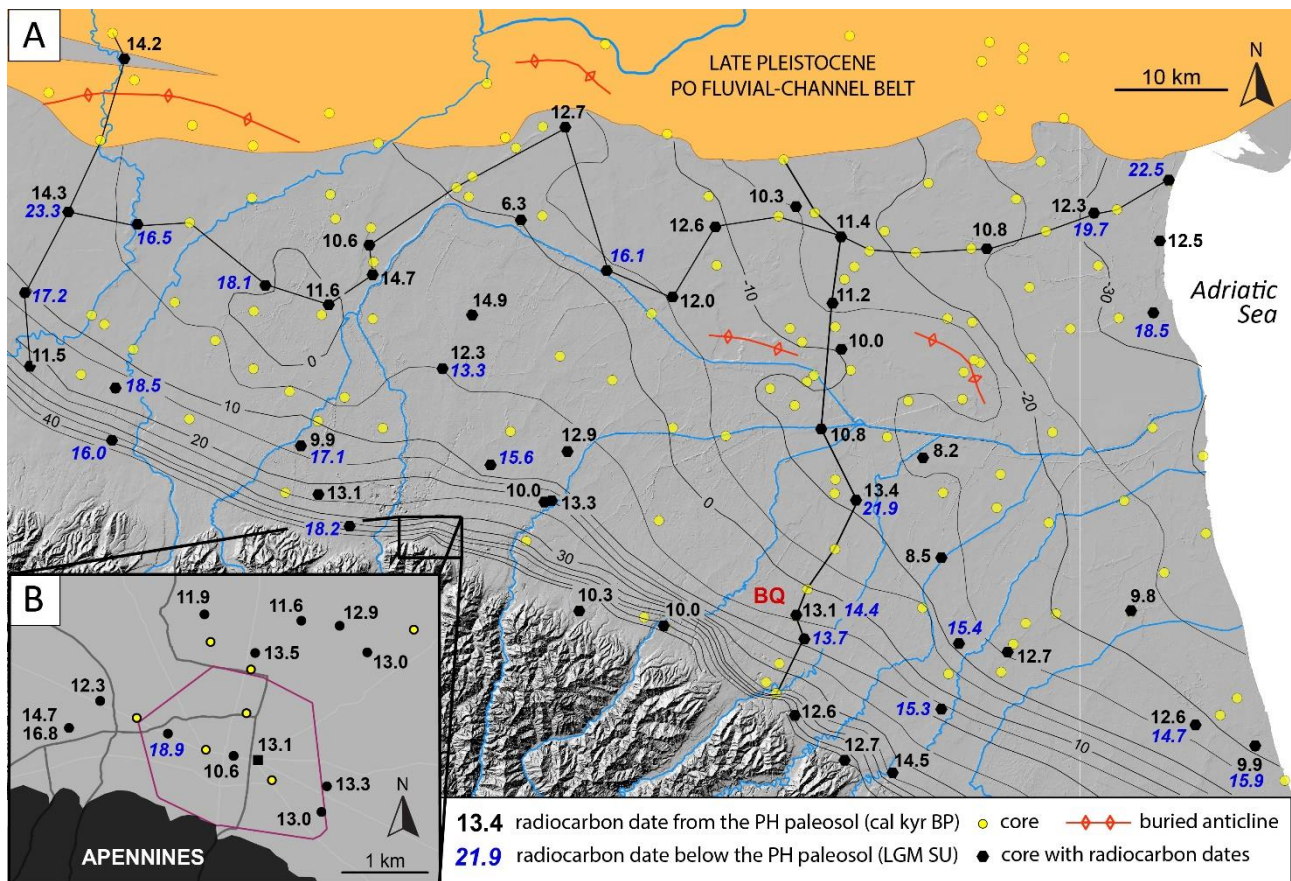


Fig. 6 – Paleosol-based correlations in the Bologna Area. LGM SU: Last Glacial Maximum Stratigraphic Unit. Location of cores in Fig 2.



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1053 Fig. 7 – A. Distribution of radiocarbon dates from bulk-soil and plant-macrofossil samples. A major
 1054 peak in dates from bulk-soil samples corresponds to paleosol PH; five minor peaks are related to
 1055 paleosols P1, P2, P3, H1 and H2. Notable is the lack of radiocarbon dated soils around 20 cal ky B.P.
 1056 (LGM). The sharp increase in radiocarbon dates from plant-macrofossils after 10 ky B.P., paralleled
 1057 by a decline in the number of dates from bulk-soil samples, reflects the onset of estuarine-deltaic
 1058 sedimentation in the distal Po Plain and the burial of paleosol PH. Red areas correspond to
 1059 interstadials, according to Bond et al., (1997) and Rasmussen et al. (2014). OD: Oldest Dryas; YD:
 1060 Younger Dryas. Light blue vertical bars indicate Henrich events (Bond et al., 1992). B. Sea-level
 1061 oscillations during the last 50 ky.



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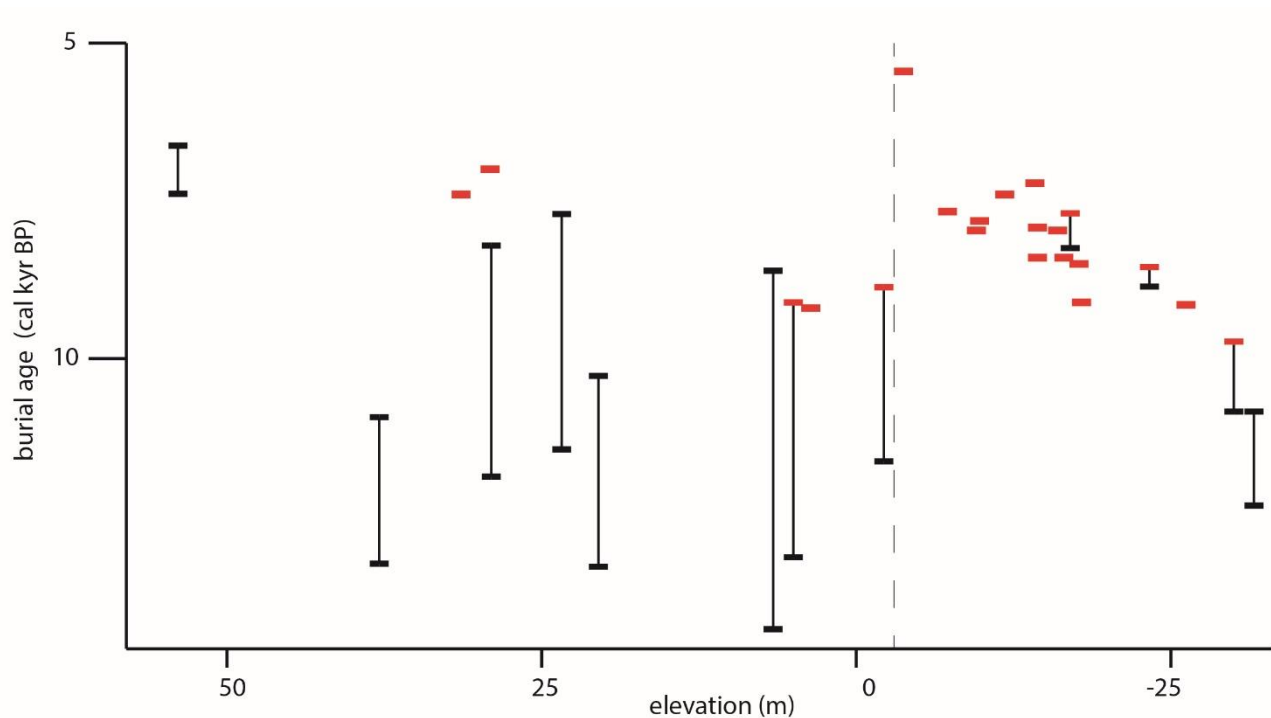
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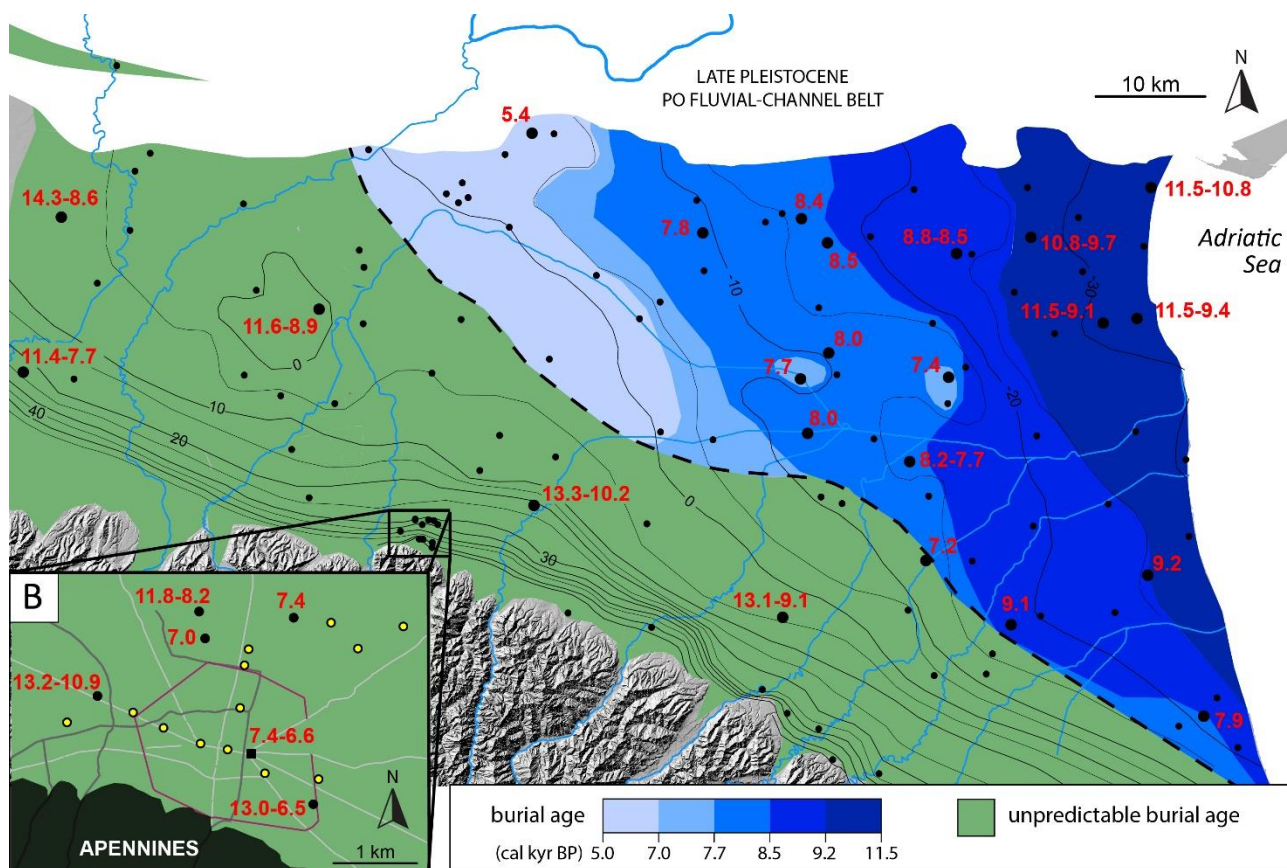
Fig. 8 – Radiocarbon dates (black numbers, cal ky B.P.) from paleosol PH (bulk soil samples) in the Po Plain (A) and in the Bologna urban area (B). Blue numbers are the youngest ages from the underlying LGM stratigraphic unit. The present-day elevation (metres above modern sea-level) of paleosol PH is depicted through 5 m-spaced isolines. BQ: Bubano Quarry.



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1069 Fig. 9 – Burial ages of paleosol PH plotted against its present-day elevation (metres above modern
 1070 sea-level). Black rectangles are radiocarbon dates from bulk soil samples. Red rectangles are
 1071 radiocarbon dates from plant macrofossils. Burial ages from samples at elevation < - 3 m (dashed
 1072 line) show an overall inverse proportionality with elevation. On the contrary, no specific trends are
 1073 observable in burial-age distribution at elevation > - 3 m.

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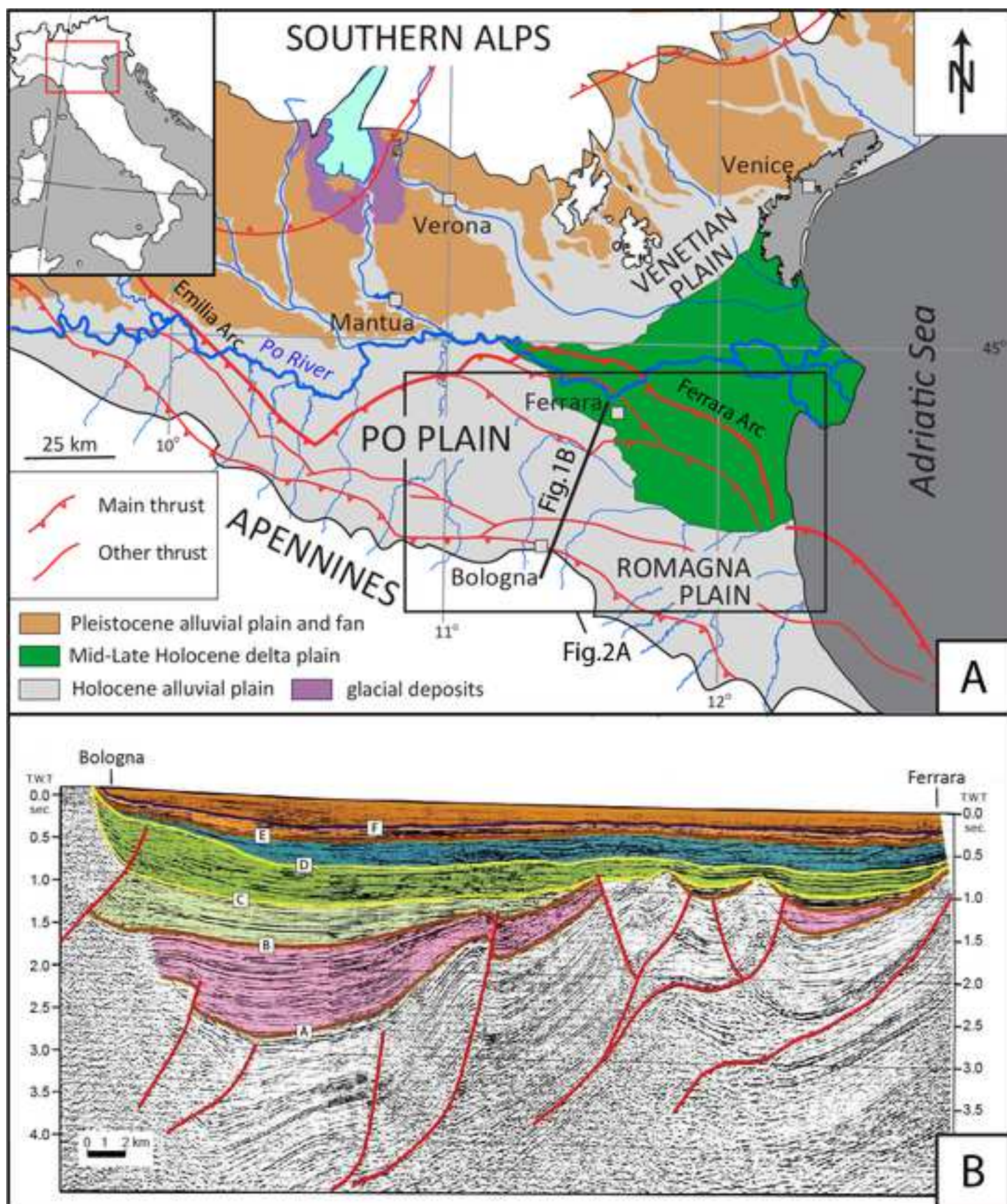
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Fig. 10 – Map showing burial ages (cal kyr B.P.) of paleosol PH in the Po Plain (A) and in the Bologna urban area (B). The shades of blue depict progressively younger burial ages upland. In the green area burial ages do not show specific spatial trends. Red numbers represent burial ages or intervals measured along single cores (black circles). The map also depicts the present-day elevation (metres above modern sea-level) of paleosol PH through 5 m-spaces isolines. Black dots are the countered data points. The dashed line represents the maximum landward extent of Holocene estuarine and delta plain deposits.

Figure 1



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Fig 3B

Fig 3A

Fig 2B

Fig 3C

Fig. 2C

Fig. 2D

Fig. 2E

Fig. 2F

Fig. 2G

Fig. 2H

Fig. 2I

Fig. 2J

Fig. 2K

Fig. 2L

Fig. 2M

Fig. 2N

Fig. 2O

Fig. 2P

Fig. 2Q

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Fig. 2AA

Fig. 2AB

Fig. 2AC

Fig. 2AD

Fig. 2AE

Fig. 2AF

Fig. 2AG

Fig. 2AH

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Fig. 2MI

Fig. 2MJ

Fig. 2MK

Fig. 2ML

Fig. 2MM

Fig. 2MN

Fig. 2MO

Fig. 2MP

Fig. 2MQ

Fig. 2MR

Fig. 2MS

Fig. 2MT

Fig. 2MU

Fig.

Figure 3

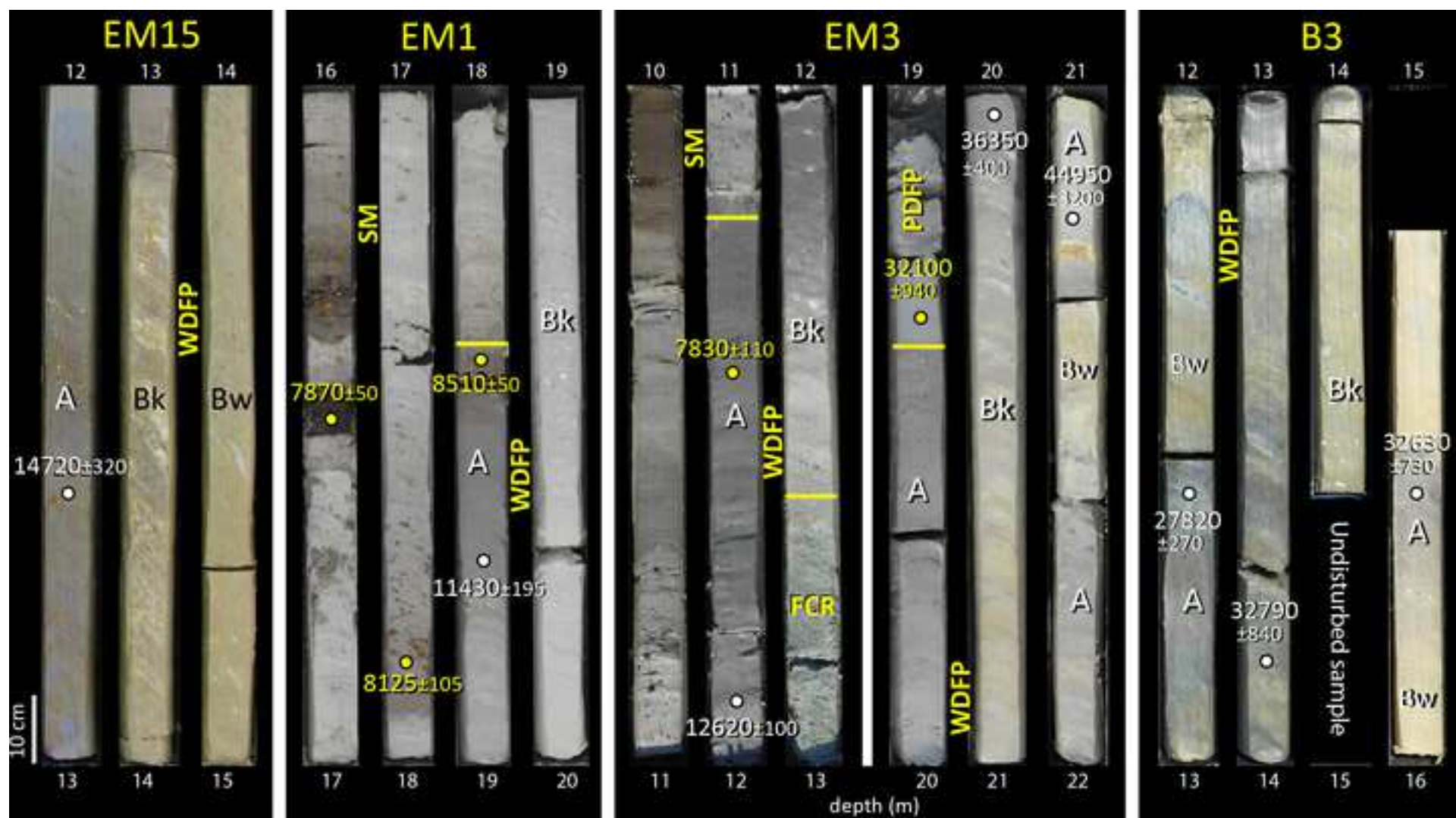


Figure 4

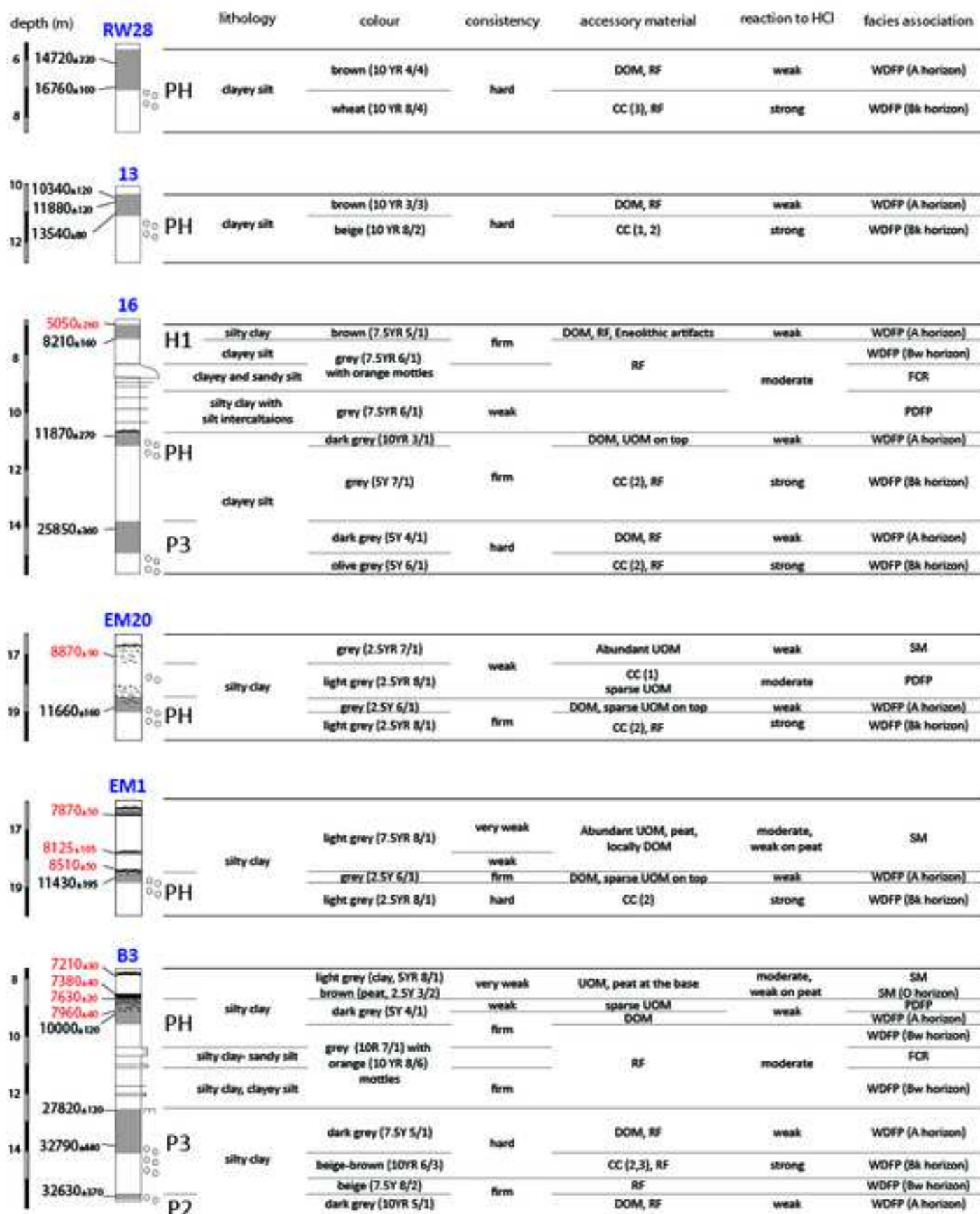


Figure 5

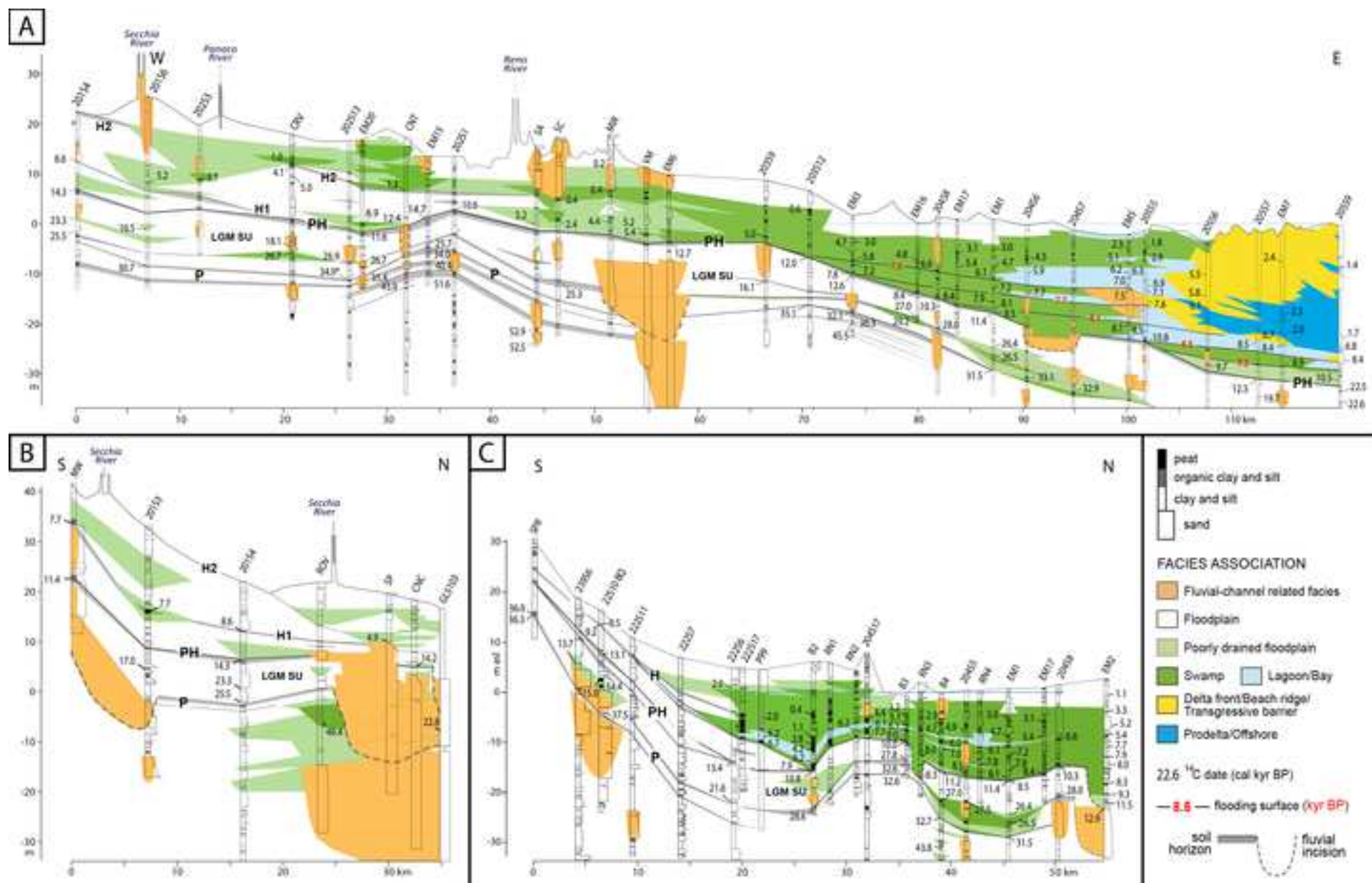


Figure 6

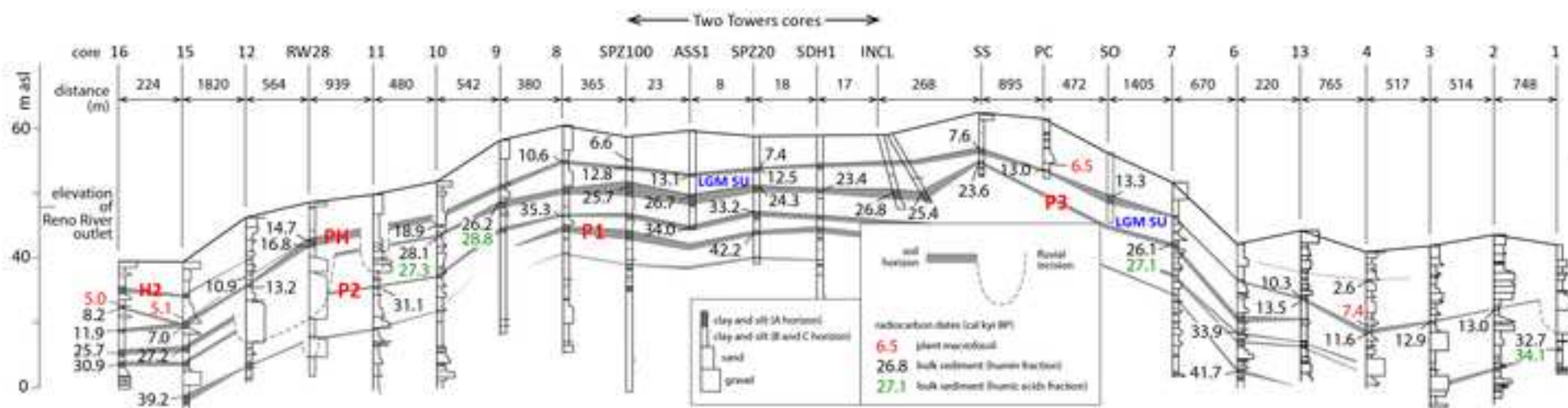


Figure 7

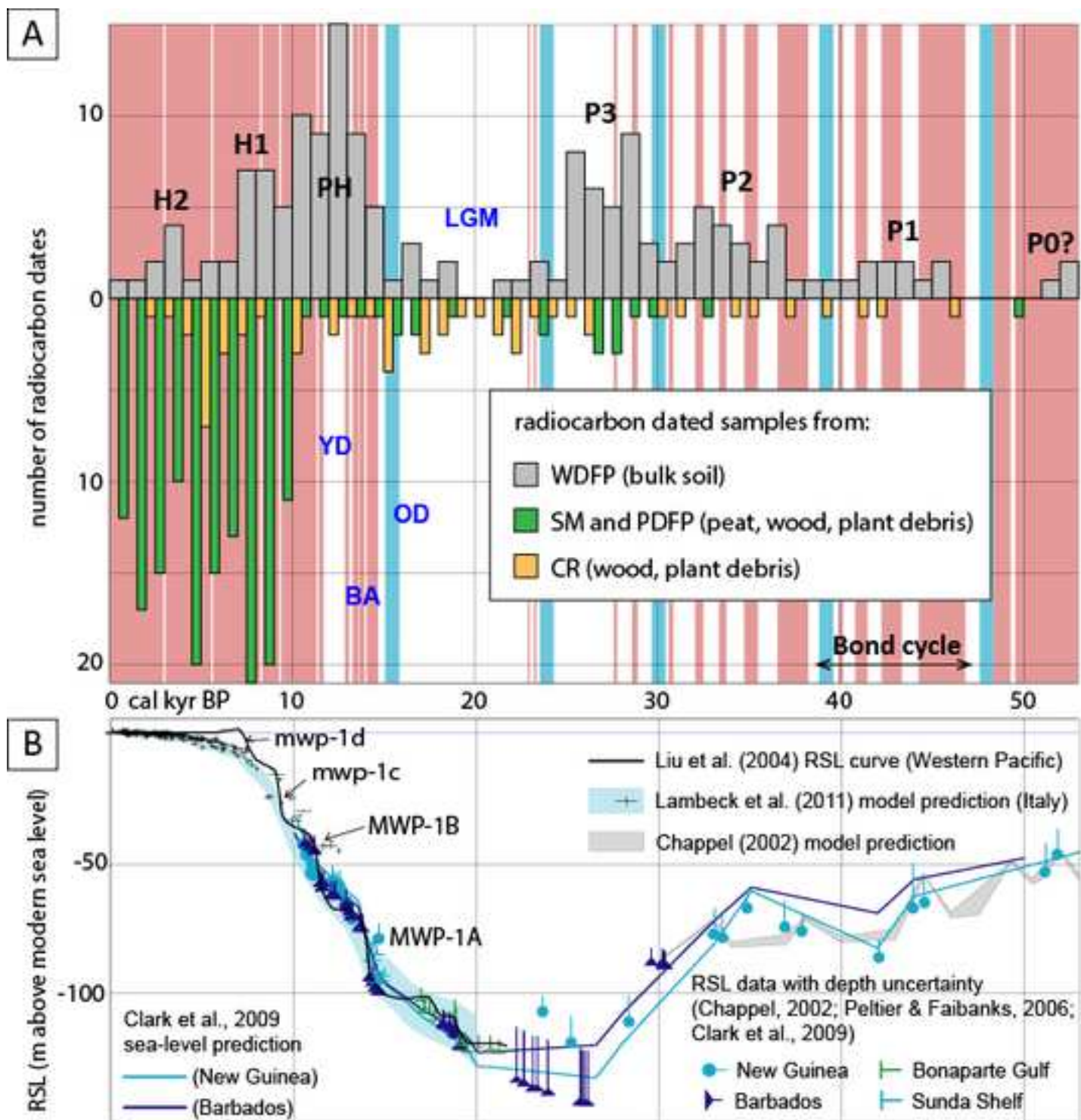


Figure 8

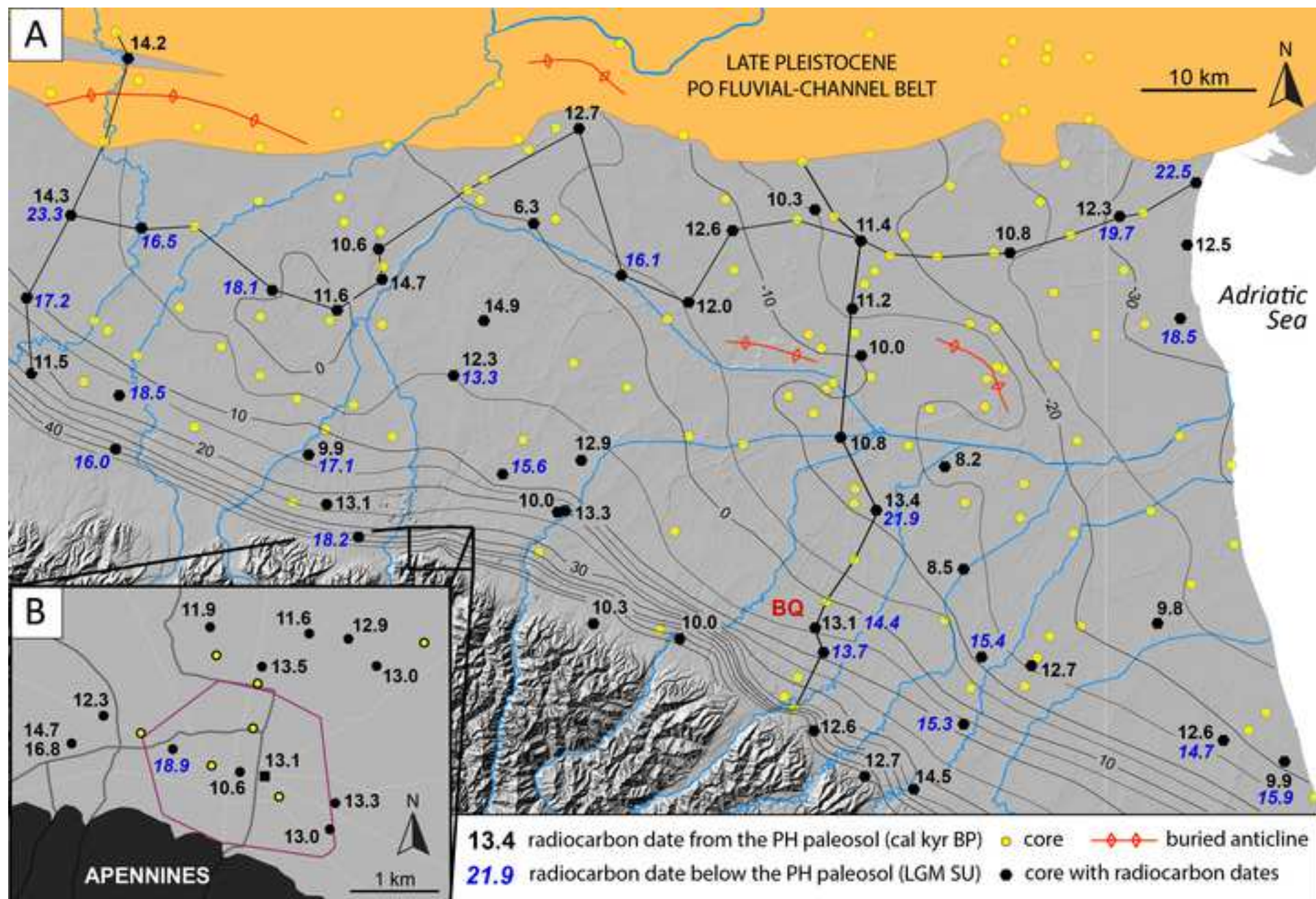


Figure 9

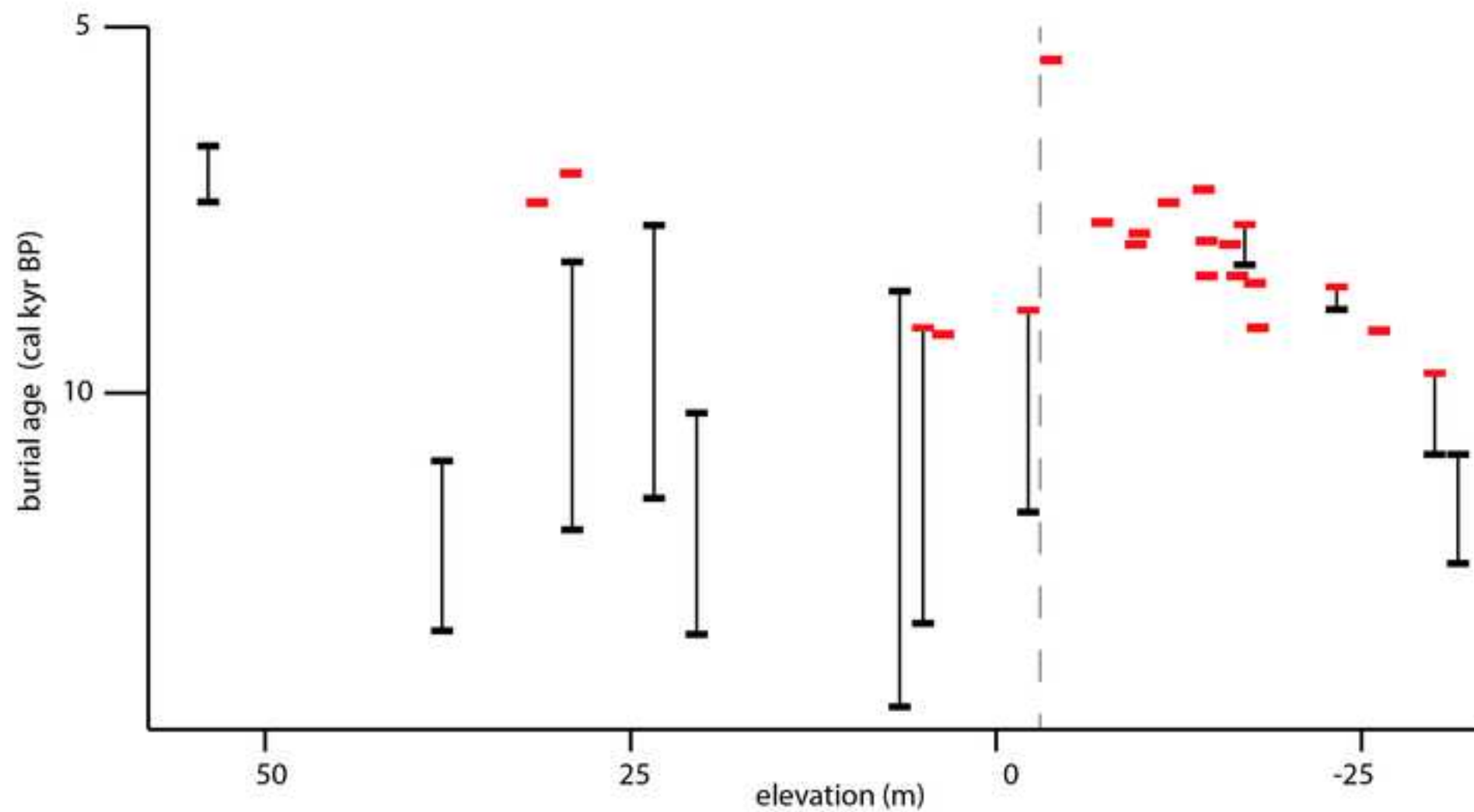
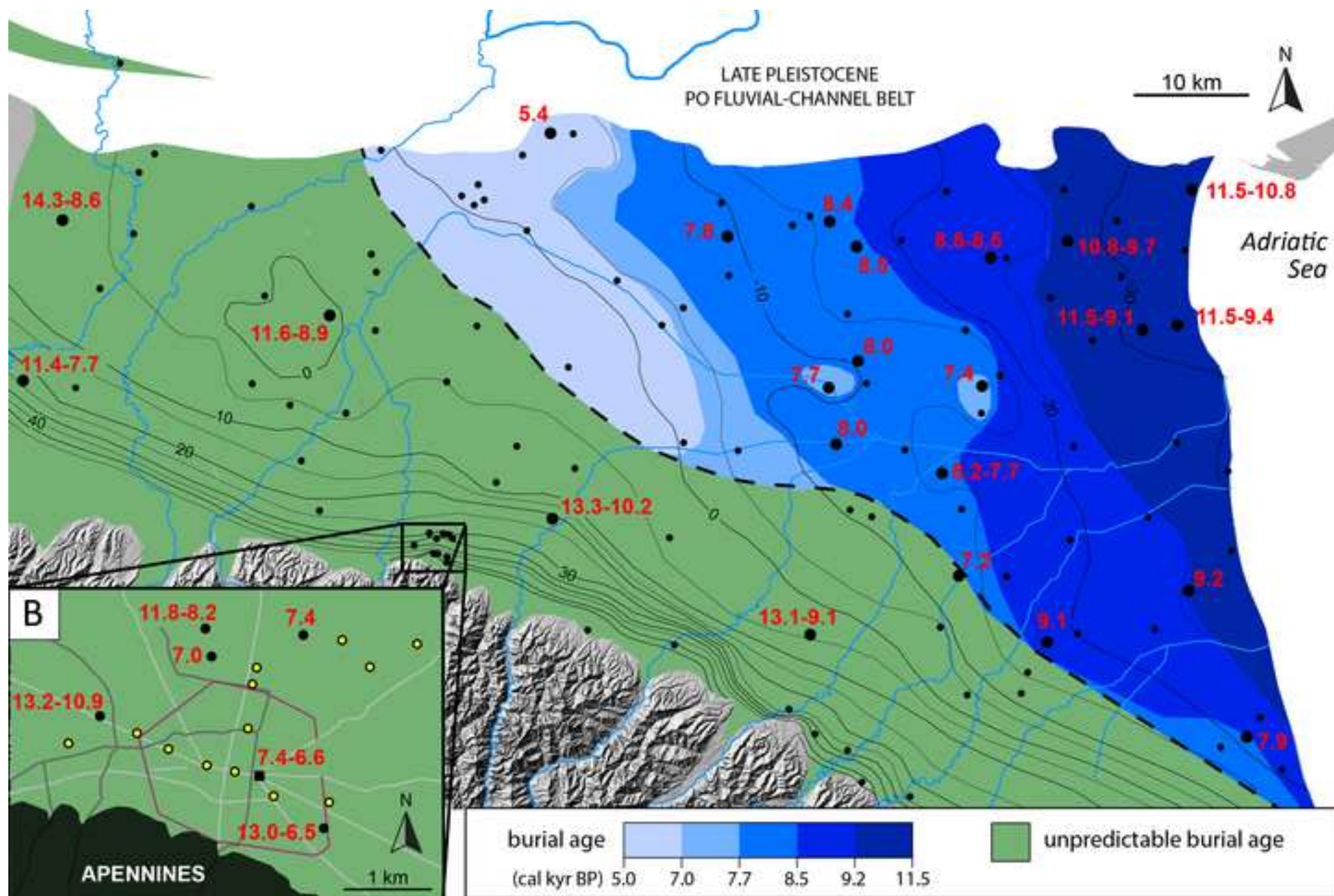


Figure 10



Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: