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1 **Changes in precipitation regimes over North America during the**
2 **Holocene as recorded by mineralogy and geochemistry of Gulf of Mexico**
3 **sediments**

4
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22
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24 mineralogy – geochemistry

25
26 **Abstract**

27 Changes in terrigenous-transfer patterns from North America toward the Gulf of Mexico via
28 the Mississippi River during the Holocene were investigated using mineralogical and
29 geochemical records from the northern Gulf of Mexico (Pigmy Basin). Clay mineralogy
30 (smectite/illite+chlorite) and geochemical signatures (K and Ti intensities) indicate
31 fluctuations in the detrital sedimentation during the Holocene in the Pigmy Basin. They likely
32 reflect alternations between at least two dominant terrigenous sources: the smectite-rich NW
33 Mississippi watershed, and the illite- and chlorite-rich Great Lakes province and NE
34 Mississippi watershed. These recurring and rapid modifications of erosional processes over
35 this period suggest changes in the hydrological regime via rainfall patterns. Such a

36 modification during the Holocene is likely linked with the rapid atmospheric reorganization
37 following the final collapse of the Laurentide Ice Sheet. Indeed, mineralogical and
38 geochemical proxies indicate east-to-west migrations of the main detrital source (from the
39 Great Lakes and northeastern province toward the northwestern province) associated with
40 Mississippi River megaflood episodes. These modifications of the main detrital sources likely
41 record migrations of the precipitation belt, which are constrained by atmospheric
42 configuration (Jet Stream, Bermuda High and Intertropical Convergence Zone position) and
43 subtropical oceanic hydrological properties (meridional extension of the Atlantic Warm Pool).
44 In the frame of previously published rainfall patterns over the Caribbean and North America,
45 our results highlight some marked modifications of moisture transfer throughout the
46 Holocene. These changes are interpreted as resulting from two atmospheric configurations
47 that have driven alternately the precipitation distribution over North America for the last 10
48 ka with an apparent cyclicity of ~ 2.5 ka. The coherent common cyclicity between the Gulf of
49 Mexico detrital parameters and Greenland atmospheric proxies over the Holocene suggests
50 that the initial external forcing was rapidly transferred latitudinally through atmospheric
51 processes.

52

53 **1. Introduction**

54 The Gulf of Mexico (GOM) is ideally located for studying the relationships between
55 high-latitude climate variability and subtropical hydrology. The hydrological properties of the
56 GOM, that further impact the Gulf Stream, result from the complex interactions between the
57 inflow of warm tropical waters originating from the Caribbean Sea through the Loop Current,
58 and from evaporation–precipitation budget and North American Rivers freshwater supply
59 (Fig. 1a). The warm waters of the GOM, Caribbean Sea, and western tropical North Atlantic
60 constituting the so-called Atlantic Warm Pool (AWP) represent the primary moisture source
61 for North America (Wang and Enfield, 2001). Moisture meridian transfer is constrained by
62 different atmospheric configurations, resulting from the respective position of the Jet Stream,
63 the Bermuda High pressure cell and the Intertropical Convergence Zone (ITCZ) (Fig. 1a;
64 Forman et al., 1995; Liu and Fearn, 2000; Knox, 2003; Harrison et al., 2003). The position of
65 the main precipitation belt is therefore likely influenced by both low- and high-latitude
66 forcing. All these oceanic and atmospheric characteristics are seasonally modulated. In the
67 western tropical Atlantic Ocean, the AWP reaches its northern position during boreal summer
68 when the ITCZ is located in its northern position, whereas these tropical waters are restricted
69 to the southeastern GOM during boreal winter when the ITCZ is situated southward (Wang

70 and Enfield, 2001; Poore et al., 2004; Nürnberg et al., 2008; Ziegler et al., 2008).

71 The hydrological characteristics of the GOM are thus also largely impacted by
72 freshwater outflow from the Mississippi River. The Mississippi and Missouri River
73 watersheds and their tributaries collect runoff from almost half the USA and carry suspended
74 detrital particles that are characteristic of the drained areas. Major Mississippi outflows may
75 modify the sea-surface salinity and impact to some extent the thermohaline circulation via the
76 Gulf Stream (Aharon, 2003; Flower et al., 2004). The Holocene climate is characterized by
77 modifications of both atmospheric and oceanic configurations following the final collapse of
78 the Laurentide Ice Sheet (LIS) evolution (Shuman et al., 2002). For instance, the Mississippi
79 River was affected during the late Holocene by megaflood episodes resulting from recurrent
80 modifications of both moisture transfer and precipitation regimes. During these episodes,
81 massive erosion of the alluvial plains promoted the remobilization of fine-grained sediments
82 and their transport toward the GOM via the Mississippi (e.g., Knox, 2000, 2003). These
83 episodes were likely controlled by the atmospheric configuration, and may have resulted in
84 changing the main provenance of the detrital supply and thus its mineralogical characteristics.

85 Recent studies (Sionneau et al., 2008; Montero-Serrano et al., 2009; Sionneau et al.,
86 2010) suggest that variations of the clay mineral assemblage deposited in the northern GOM
87 mainly reflect changes in the respective contributions of four main mineralogical provinces on
88 land (Fig. 1b): (1) the northwestern Mississippi and Missouri rivers watershed is characterized
89 by high smectite content (SN50%, Ib30%, Kb20%, Cb14%), (2) the northeastern province
90 mainly delivering illite and chlorite (Sb20%, IN30%, Kb25%, CN12%), (3) the kaolinite-rich
91 southeastern part of the United States (Sb30%, Ib20%, KN30%, Cb28%), and (4) the Brazos
92 River and southwestern Mississippi River watersheds is dominated by illite and kaolinite
93 (Sb40%, IN30%, KN20%, Cb8%). More details on the clay mineral distributions in and
94 around Mississippi River watershed are discussed by Sionneau et al. (2008). The letters S, I,
95 C and K denote smectite, illite, chlorite and kaolinite, respectively. The mineralogical and
96 geochemical characteristics of the detrital fraction of the sediment can thus be used to trace
97 the modifications of the main detrital source associated with major flooding episodes and to
98 constrain the main factors triggering such catastrophic events.

99 In this article we present a mineralogical and geochemical record of Holocene climate
100 variability for the last 10 ka from core MD02-2553 (27°11.01"N, 91°25.00"W, water depth
101 2259 m) recovered in the Pigmy Basin. This basin, situated on the Louisiana continental slope
102 around 250 km southwest of the present-day Mississippi Delta, is suitably located to record
103 both the terrigenous input from the North American continent and the tropical oceanic

104 influences via the Loop Current (Fig. 1a). The basin is approximately 20 km-long, 7 km-wide,
105 and trends northeast to southwest (Fig. 1b). Thus, using proxies of terrigenous supply in the
106 Pigmy Basin during the Holocene, the main objectives are: (1) to determine changes in the
107 North American sedimentary provenance throughout the Holocene, (2) to document the main
108 changes in rainfall distribution over North America, and (3) to constrain the links between
109 modifications of both high-latitude and subtropical domains, in order to infer possible
110 synoptic scenarios or configurations of the atmosphere–ocean–continent interactions during
111 the Holocene, and to further constrain the Holocene variations in summer moisture transfers
112 across North America.

113

114 **2. Materials and methods**

115 *2.1. Samples and chronology*

116 The samples were taken from the 10.3 m long core MD02-2553 (Calypso Square)
117 collected on the center of the Pigmy Basin during the 2002 PAGE (Paleoceanography of the
118 Atlantic and Geochemistry) cruise of the research vessel Marion Dufresne, as part of the
119 International Marine Past Global Changes Study (IMAGES) program (Fig. 1b). The sediment
120 is mainly composed of massive or faintly laminated silty to clayey mud (Fig. 1c). Black
121 shading related to accumulation of organic material is recurrent throughout the core. The
122 uppermost 155 cm of the core is composed of sandy to silty clay with foraminifers and
123 coccoliths, whereas the lower part contains clays with foraminifers that become scarce below
124 400 cm. One distinct upward grading, foraminifer-rich, sandy layers interpreted as small
125 turbidites occurring in the core at 298–300 cm depth has been removed from the record, as it
126 corresponds to local sedimentological processes rather than fluvial discharge.

127 The chronology for the upper 359 cm of core MD02-2553 is based on sixteen
128 accelerator mass spectrometry (AMS) ¹⁴C radiocarbon dates from mixed planktic
129 foraminifers published by Poore et al. (in press) (Table 1, Fig. 1c). All ages were converted
130 into calendar years with the CALIB software (Stuiver and Reimer, 1993, version 5.0.2;
131 <http://calib.qub.ac.uk/calib>), using the calibration curve Marine04 (Hughen et al., 2004). All
132 AMS¹⁴C ages were corrected using a constant reservoir age of 400 yr ($\Delta R=0$) because it
133 provides consistency with both modern values (Bard, 1988) and with previous
134 paleoceanographic studies from the GOM (e.g., Flower et al., 2004; Meckler et al, 2008;
135 Nürnberg et al., 2008; Montero-Serrano et al., 2009). Calibrated ages were plotted against
136 core depth (Fig. 2), and a least squares regression ($r^2=0.996$) indicates a linear sedimentation
137 rate of 35.9 cm/ka (within the errors of the calibrated dates; 1 ka=1000 cal yr BP) and a core-

138 top age of 0 yr BP.

139

140 *2.2. Analytical methods*

141 The Holocene section of the core MD02-2553 (the upper 359 cm) was studied at high
142 resolution (average sample resolution of ~47 yr) for clay mineralogy and grain size. Inorganic
143 geochemistry was studied for some major elements (K and Ti) at 1 cm resolution (average
144 sample resolution of ~28 yr) using the XRF core scanner. Complementarily, trace and rare
145 earth element (REE) concentrations were determined at lower resolutions, with average
146 sample resolution of 555 yr.

147

148 *2.2.1. Clay mineral analysis*

149 Clay mineral associations were studied using X-ray diffraction following the protocol
150 of Bout-Roumazel et al. (1999). The analyses were run from $2.49^\circ 2\theta$ to $32.49^\circ 2\theta$ on a
151 Philips PW 1749 diffractometer (copper anode; 40 kV; 25 mA intensity and $1^\circ 2\theta/\text{minute}$
152 speed). Three X-ray diagrams were performed, after air-dried sample, ethylene glycol vapour
153 saturation for 12 h and heating at 490°C during 2 h. Semi-quantitative estimation of clay
154 mineral abundances (smectite, illite, chlorite and kaolinite), based on peak areas, was
155 performed using the Macintosh MacDiff® 4.2.5 software (Petschick, 2000). The error on the
156 reproducibility of measurements is estimated to be 5% for each clay mineral, as checked by
157 analysis of replicate samples.

158

159 *2.2.2. Grain-size distribution*

160 Grain-size analyses were carried out on the carbonate-free fraction of the sediment, in
161 order to focus on the detrital fraction, using a Malvern Mastersizer 2000 laser diffractometer.
162 Sample preparation and optical settings for the Mastersizer 2000 followed the method
163 described by Montero-Serrano et al. (2009). The main grain-size parameter reported here is
164 the mode (μm , most frequent grain size). The precision was ~4%, expressed as the coefficient
165 of variation of replicate determinations.

166

167 *2.2.3. Elemental geochemistry*

168 K and Ti abundances were obtained on the U-channels of the core using the Avaatech
169 XRF core scanner at the Université Bordeaux 1 (EPOC, UMR-CNRS 5805). The U-channels
170 used were designed and developed at the Paleomagnetism and Environmental Magnetism
171 laboratory of the LSCE (Gif-sur-Yvette, France). The U-channels surface was cleaned and

172 covered with Ultralene® X-ray transmission foil to avoid desiccation of the sediment and
173 contamination of the measurement unit. To obtain statistically significant data we used a 30 s
174 count time, a 10 kV X-ray voltage and a current of 400 mA. Acquired XRF spectra were
175 processed with the WinAxil and WinBatch software packages. The resulting data are
176 expressed as element intensities in counts per second (cps). Precisions were better than 2%, as
177 checked by international standards powder samples. For further technical details on the XRF
178 scanning technique see Richter et al. (2006).

179 In addition to XRF core scanner, trace and rare earth element (REE) concentrations
180 were determined by inductively coupled plasma optical emission spectrometry (ICP-OES)
181 and inductively coupled plasma mass spectrometry (ICP-MS), at Activation Laboratories Ltd.
182 (Ancaster, Canada). Samples were mixed with a flux of lithium induction furnace. Molten
183 sample was immediately poured into a solution of 5% nitric acid (HNO₃) containing an
184 internal standard, and mixed continuously until completely dissolved. The analytical accuracy
185 and precision were found to be better than 5–10% for trace element and 5% for REE, as
186 checked by international standards and analysis of replicate samples.

187 Trace-metal (TM) concentrations are expressed in terms of enrichment factors
188 (EFTM) where the Al-normalized metal concentration is compared to the average shale
189 values of Wedepohl (1971, 1991): $EF_{TM} = TM/Al_{sample} : TM/Al_{average\ shale}$. $EF_{TM} > N1$ suggests
190 enrichment relative to average shale but authigenic enrichments can be considered when EF_{TM}
191 exceeds 5 (Tribovillard et al., 2006). NASC values by Gromet et al. (1984) are used for
192 normalization of the REE.

193 In this study, K and Ti intensities are used as proxies of the detrital sediment sources,
194 complementary to clay mineral proxies. In addition, the REE abundance patterns provide
195 fingerprints associated with detrital fraction of the sediment which in turn represents the bulk
196 composition (e.g., Montero-Serrano et al., 2009).

197

198 *2.3. Spectral analyses*

199 We performed time series analysis in order to evidence any cyclicity in the Pigmy
200 basin clay mineral variations and to investigate their correlation with high-latitude climatic
201 records, using the software package AnalySeries 2.0.4 (Paillard et al., 1996; [http://
202 www.lsce.ipsl.fr/logiciels/index.php](http://www.lsce.ipsl.fr/logiciels/index.php)). We used two different spectral analysis methods a non-
203 parametric Multi-Taper method, which provides high spectral resolution even for short time
204 series (Thompson, 1982) and the high confidence Blackman–Tukey method (Blackman and
205 Tukey, 1958) in order to improve accuracy and to prevent any bias due to methodological

206 artefact. All time series were evenly resampled with a 0.045-ka interval and linear trends were
207 removed prior to spectral analysis. The sample interval results in an average time resolution
208 of 0.045 ka. Thus the lowest theoretical period (Nyquist period) that could be resolved is
209 always below 0.167 ka (two times maximum sampling period). Spectral analyses were
210 calculated for the b5.88 ka (1/0.17 ka) high-pass filtered data, according to the studied
211 window 9.99 ka. The multi-taper method (MTM; Ghil et al., 2002) was performed using two
212 tapers and a bandwidth resolution of 0.3 ka. The Blackman–Tukey cross-spectral analysis
213 (Paillard et al., 1996) was performed using a Bartlett-type window, high resolution (50% of
214 the series length) with a resulting 0.30 ka⁻¹ bandwidth. Results of the spectral analysis are
215 presented as spectral density. Each frequency band is reported taking as center the observed
216 maximum spectral density for specific band. The mean Blackman–Tukey coherency and
217 phase were calculated by cross-spectral analysis between the clay mineral distribution
218 [S/(I+C)] in the Pigmy Basin and GISP2 sea-salt Na record (O'Brien et al., 1995; Mayewski et
219 al., 2004). Coherency is considered significant (at the 95% level) if larger than 0.67.
220 Averaged coherency is calculated on the 0.30 ka bandwidth centered on S/(I+C) maximum
221 power spectrum. Phases are reported only for the more significant bands (highest spectral
222 density and significant coherency). Phases in radians were converted to kiloyears (one
223 period=360°=2Pi radian) for each of the frequency bands.

224 All analytical data presented are available through the World Data Center-A for
225 Paleoclimatology.¹

226

227 3. Results

228 3.1. Clay mineralogy and sediment grain size

229 The clay mineral fraction is composed of 56–84% smectite, 7–20% illite, 3–14%
230 chlorite and 3–13% kaolinite (Fig. 3). In general, smectite distribution is inversely correlated
231 to illite and chlorite. The clay mineral composition displays some characteristic oscillations
232 between smectite-rich intervals (for example between 2.9 and 1.6 ka) and illite+ chlorite-rich
233 intervals (for example between 3.8 and 2.9 ka).

234 All samples are characterized by a unimodal grain-size distribution. The sediments are
235 mainly composed of cohesive-silt (3.5 μm <mode> 5.1 μm). The grain-size mode (μm) shows

¹ 1 Supporting data are available electronically at World Data Center (WDC Paleo online archive; e-mail: paleo@mail.ngdc.noaa.gov, URL: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/montero-serrano2010/montero-serrano2010.xls).

236 a steady and rather constant distribution throughout the Holocene (Fig. 4a). The important
237 point is that the rather smooth distribution in the grain-size mode suggests that the
238 mineralogical and elemental variations within the studied core are not due to the sorting of the
239 sediment (e.g., Fig. 4b–d).

240

241 *3.2. Geochemical composition of the sediment*

242 The XRF core scanner provides a record of the main geochemical variations
243 characterizing the sediments from the Pigmy Basin. K and Ti records display similar trends,
244 (Fig. 4c,d consistent with the observed clay mineral oscillations, i.e., K and Ti intensities are
245 maximum over the illite+chlorite-rich intervals (Fig. 4b–d)). Fig. 4 also shows the opposed
246 relationship between K and Ti and the smectite proportion within the sediment. Elemental
247 intensities are thus interpreted to reflect changes in the clay mineral assemblage of the
248 terrigenous fraction. Trace-metal enrichment factors do not show any significant variations
249 (0.5 to 2.2) (Fig. 5a). NASC-normalized REE patterns do not show any striking features (Fig.
250 5b), except for a general slight enrichment in light REE (LREE: La–Nd) over heavy REE
251 (HREE: Tb–Lu).

252

253 **4. Interpretation and discussion**

254 *4.1. Main characteristics of Holocene sedimentary records in the Pigmy Basin*

255 The calcareous biogenic fraction in the Pigmy Basin sediments is relatively low
256 (CaCO_3 25%; not shown) indicating that the Holocene sedimentation is mostly terrigenous,
257 with a relatively limited, autochthonous biogenic contribution. In addition, detrital carbonate
258 contributions in the Pigmy sediments are negligible, as evidenced by the scanning electron
259 microscopy (SEM) analysis of silt-size particles from the same core (Flocks and Swarzenski,
260 2007). Furthermore, trace-metal enrichment factors suggest that the authigenic phases in the
261 Pigmy Basin are negligible (Fig. 5a). The absence of any significant REE fractionation when
262 normalized to NASC in Pigmy Basin sediments, as observed in other basins from the GOM
263 (Flocks and Swarzenski, 2007), indicates a smoothed detrital source (Fig. 5b). The similarity
264 of REE distributions in Pigmy Basin sediments when compared with Mississippi River
265 suspended loads (Goldstein and Jacobsen, 1988; Elderfield et al., 1990) indicates the
266 dominant influence of the Mississippi River (Fig. 5b). Our results thus suggest that the Pigmy
267 Basin is representative of the sedimentation in the offshore part of the GOM in that it mainly
268 collects land-derived particles delivered by the Mississippi River which receives main
269 discharges from the Missouri (NW)+Ohio (NE) rivers system (e.g., Sionneau et al., 2008) and

270 drains almost half of the conterminous USA (Fig. 1b). In other words, the Pigmy Basin is an
271 appropriate recorder of the land-to-sea transfer, from North America to the GOM.

272 Mineralogical and geochemical data both suggest that Holocene detrital sedimentation
273 mainly results from the contributions of two different sources. The first source is
274 characterized by its high smectite content whereas the second contributor is enriched in illite
275 and chlorite with high K and Ti intensities (Figs. 3 and 4). According to recently published
276 clay mineral distribution maps (Sionneau et al., 2008), the first end-member corresponds to
277 the northwestern Mississippi and Missouri rivers watershed province and the second, one is
278 likely the northeastern Great Lakes province.

279 During the early Holocene, the Mississippi River discharge capacity was significantly
280 reduced compared with the last deglaciation (Fig. 2), as evidenced in the Pigmy Basin record
281 by a decrease of the sedimentation rate from about 397–200 during the Meltwater Spike
282 (Montero-Serrano et al., 2009) to 25–36 cm/ka during the Younger Dryas and Holocene. This
283 decrease is due to a drastic decrease in the glacial erosional processes linked to the decay of
284 the Laurentide Ice Sheet or LIS (Montero-Serrano et al., 2009). The modifications of the LIS
285 extent (e.g., Fig. 8a) played a major role in climate change in the Northern Hemisphere
286 between 10 and 5 ka, resulting in the rapid warming of the Northern Hemisphere interrupted
287 by the cold 8.2 ka event (Mayewski et al., 2004). Consequently, the observed variations in the
288 respective contributions of these two dominant sources (smectite vs. illite+chlorite) during the
289 early Holocene may be related to the LIS extent changes.

290 Any major modification of the dominant terrigenous sources that occurred during the
291 middle to late Holocene cannot be driven by the LIS that was considerably reduced by this
292 time. Significant modifications are more likely related to modifications of the continental
293 drainage patterns on the Mississippi River system in response to migrations of the main
294 precipitation belt over North America (Knox, 2000, 2003). The mineralogical and
295 geochemical record of core MD02- 2553 from the Pigmy Basin will thus be here interpreted
296 in relation with the Holocene climatic variability.

297

298 *4.2. The variability of Mississippi River runoff during the Holocene*

299 Successive intervals enriched in smectite [$S/(I+C) > 4$] characterize Holocene Pigmy
300 Basin records (Fig. 6c). These intervals at 10–8.9, 8–6.2, 5–3.8, 2.9–1.6, 0.8–0.3 ka coincide
301 with large Mississippi floods (Fig. 6a) described in the central part of North America (Knox,
302 2000, 2003). Note that K intensities show a parallel trend when compared with illite and an
303 opposite trend when compared with smectite, reflecting its affinity for K-bearing illite in

304 sediments from Pigmy Basin (Fig. 6b). These observations suggest that the mineralogical
305 signature is indeed influenced by erosional processes in the NW Mississippi watersheds.

306 These Holocene flood episodes, occurring as the ice-sheet had almost entirely
307 vanished, likely resulted from heavy rainfall periods over the central part of North America
308 (Knox, 2003). Additionally, the smectite-rich interval observed in the Holocene in the Pigmy
309 Basin was already described in the Orca Basin (Sionneau, 2008) and interpreted as a period of
310 severe megafloods (Brown et al., 1999). The correlations between continental and marine
311 records indicate that these megaflood events represent regional-scale changes in the
312 hydrologic cycle over North America.

313 We hypothesize that the variability of the Mississippi River regime during the
314 Holocene (e.g., flood episodes) evidenced by both mineralogical and geochemical records
315 reflects primarily variations in the migration of the precipitation belt over the North American
316 continent. According to this scenario, these variations have been controlled by changes in
317 atmospheric circulation patterns and the associated modifications of the meridian moisture
318 transfer from the GOM to the North American continent. This moisture transfer and more
319 generally the hydrological variability directly depend on the evaporation (E)–precipitation (P)
320 balance over the GOM (Knox, 2000; Harrison et al., 2003) where increased evaporation leads
321 to enhanced precipitation over the North American continent (e.g., Flannery et al., 2008). As
322 the E–P balance is linked to insolation, and sensitive to solar irradiance variability (Perry and
323 Hsu, 2000), we also hypothesize that changes in solar variability may ultimately affect rainfall
324 patterns over North America through ocean–atmosphere interactions. We will further test this
325 hypothesis by comparing our records with previously published climate-related records from
326 the Caribbean, GOM and North America.

327

328 *4.3. Precipitation distribution and atmospheric configuration during the Holocene*

329 The interaction of three main air masses controls the general climatic patterns over the
330 North American continent: the warm and moist GOM air mass, the dry and mild Pacific air
331 mass, and the dry, cold Arctic air mass (Knox, 2000). The location of the boundary between
332 these air masses in North America, and therefore of the main position of the precipitation
333 front, is controlled by the respective position and extension of the Jet Stream, and of the
334 Bermuda High pressure and Thermal Low pressure cells (Forman et al., 1995; Liu and Fearn,
335 2000; Knox, 2003). In the northwestern Mississippi river watershed, where the smectite-rich
336 intervals are associated with paleo-flooding episodes (Fig. 6), present-day average annual
337 precipitation ranges between about 498 and 568 mm with about 70% of the annual amount

338 falling during the warm season from April to September (boreal summer;
339 <http://www.rssweather.com/climate/>).

340 Here we attempt to use clay mineral record from the Pigmy Basin to retrace the
341 summer migrations of the precipitation belt over the central part of North America during the
342 Holocene. The contributions of smectite vs. illite+chlorite [S/(I+C) ratio] from the Pigmy
343 Basin are used to document the continental-scale shift of the precipitation belt over the central
344 part of North America. Additionally, we use previously published palynological, isotopic and
345 geochemical data from both continental and marine series (Hodell et al., 1991; Haug et al.,
346 2001; Willard et al., 2005; Kennedy et al., 2006; Denniston et al., 2007; Nordt et al., 2008;
347 Mueller et al., 2009) in order to constrain the two proposed configurations of the Holocene
348 variations in summer ocean–continent moisture transfer (Forman et al., 1995; Knox, 2000,
349 2003; Liu and Fearn, 2000).

350 The signal of Holocene climatic conditions over North America is reconstructed using
351 different proxies. A shift toward positive values in the $\Delta\%C4$ records of buried soils from the
352 North American Great Plains (Nordt et al., 2008) and in the $\delta^{13}C$ records of stalagmites from
353 the Devil's Icebox Cave (Denniston et al., 2007), is interpreted to indicate increased
354 abundances of C4 grasses ($\Delta\%C4$) and hence warming and drying conditions; conversely
355 negative values suggest wetter conditions. Increased aridity is inferred from reconstructed
356 increases in percent of *Quercus* pollen from the Chesapeake Bay, (Willard et al., 2005).

357

358 *4.3.1. Configuration 1*

359 The mineralogical and geochemical signatures of the smectite-rich intervals (10–8.9,
360 8–6.2, 5–3.8, 2.9–1.6, 0.8–0.3 ka; Figs. 6 and 7e) indicate that the major flood events were
361 derived primarily from northwestern Mississippi and Missouri rivers watersheds. These
362 results suggest that the precipitation belt was located over the northwestern province and that
363 the main moisture transfer reached the central part of North America during these periods.
364 Negative $\Delta\%C4$ excursions from the North American Great Plains (Fig. 7d) also suggest an
365 enhanced moisture flux from the GOM toward the central part of North America, whereas the
366 strong increase in the *Quercus* pollen content from the Chesapeake Bay (Fig. 7b) in the
367 northeastern region of the North America, indicates the development of drought conditions
368 along the eastern coast of North America. Furthermore, several northeastern USA lakes also
369 experienced low level during these intervals implying a widespread drought (e.g., Newby et
370 al., 2000; Shuman et al., 2002). According to configuration 1, the moisture distribution

371 evidenced during these intervals implies that the Jet Stream and the Bermuda High were
372 located to their northernmost and southwestern most positions, respectively, while the low
373 pressure was displaced eastward (configuration 1, Fig. 9c) in agreement with configurations
374 proposed by Forman et al. (1995), Liu and Fearn (2000) and Knox (2000, 2003). At present,
375 this synoptic pattern promotes transfer of moist air from the GOM and nearby tropical waters
376 toward the central part of North America (Knox, 2000, 2003).

377

378 *4.3.2. Configuration 2*

379 The intervals 8.9–8, 6.2–5, 3.8–2.9 and 1.6–0.8 ka are characterized by low S/(I+C)
380 ratio (Fig. 7e) indicating low precipitation on the smectite-rich northwestern province. This
381 suggests an eastward transfer of the main moisture pattern, which is consistent with the
382 relative increase in illite and chlorite. Positive $\Delta^{13}C_4$ and $\delta^{13}C$ excursions from the North
383 American Great Plains (Fig. 7d) and the Devil's Icebox Cave, central Missouri (Fig. 7c) also
384 suggest dry conditions over the central part of North America. On the contrary, the strong
385 decrease in the Quercus pollen content from the Chesapeake Bay (Fig. 7b) suggests enhanced
386 moisture abundance in the mid- Atlantic region (Willard et al., 2005). All these observations
387 enable us to propose a second configuration (configuration 2) of the main moisture transfer
388 over the successive intervals depleted in smectite (Fig. 9d). Investigations on the regional
389 hydrologic responses to large-scale atmospheric circulation patterns during the Holocene
390 (e.g., Forman et al., 1995; Knox, 2000, 2003; Liu and Fearn, 2000; Harrison et al., 2003;
391 Goman and Leigh, 2004) suggest that the Jet Stream and the Bermuda High were located to
392 the south and northeast respectively constraining the inflow of moisture along the eastern
393 coast of North America and a reduced flux toward the central part of North America. The
394 reconstructed Jet Stream pattern shown in Fig. 9d with a main meridional component and a
395 noticeable zonal component would likely lead to warm and dry summer conditions in the
396 central part of North America, while increased precipitation and flooding occurred in the
397 eastern area (Knox, 2000, 2003).

398

399 *4.3.3. Configuration modulation*

400 The two proposed configurations are mainly based on GOM and North American
401 records, i.e. related to the position of the Jet Stream and high- and low-pressure cells. In order
402 to improve these scenarios, we attempt to take into account the variations of the ITCZ and
403 AWP that may modulate moisture transfer throughout the Holocene. The ITCZ migration and
404 the temporal dynamics of the AWP can be monitored using paleoclimate records from the

405 circum-Caribbean region and northern GOM (Figs. 1a and 8a–c,f). The relative abundance of
406 the warm water species *G. sacculifer* and the seasurface temperature ($SST_{Mg/Ca}$) values in the
407 GOM are related to the inflow of Caribbean water into the GOM. Maximum transport of
408 Caribbean surface waters into the GOM, and therefore enhanced moisture transfer toward the
409 central part of North America (Lovvorn et al., 2001), are associated with both a more
410 pronounced AWP and a northward migration of the average position of the ITCZ.

411 In this context, the increase abundance of the warm water species *G. sacculifer*
412 together with high $SST_{Mg/Ca}$ values from the GOM (Fig. 8c,f) and more negative $\delta^{18}O$ values
413 from the Miragoane Lake suggest that during the early Holocene, the AWP reaches its
414 maximum size and intensity, in phase with a northward most position of the ITCZ, compared
415 with the late Holocene (Fig. 8c,f). This position led to enhanced precipitation in the circum-
416 Caribbean region and decreased the transport of precipitable water ($E > P$) toward the North
417 American continent (Fig. 9c–d). However, during the late Holocene, a less established AWP,
418 in combination with a southward position of the ITCZ (based on lower levels of *G. sacculifer*
419 and low $SST_{Mg/Ca}$ in the GOM, and more positive $\delta^{18}O$ values from the Miragoane Lake; Fig.
420 8b–c) likely promoted drought in the Caribbean region (Figs. 8a and 9e–f), increasing the
421 availability of precipitable water vapour ($E > P$) transported toward the North American
422 continent (Wang et al., 2008). Thus during the past 3 ka, configuration 1b (Fig. 9e) is thought
423 to be responsible for the more important flood events and catastrophic hurricanes that affected
424 the central part of North America (e.g., Knox, 2000, 2003; Liu and Fearn, 2000).

425

426 *4.4. Clay mineralogy variations during the Glacial–Holocene transition*

427 The Holocene clay mineralogy variability in the Pigmy Basin sediments is similar in
428 range with the Glacial–Holocene transition variability. There is a slight difference during the
429 main meltwater discharge episode during the deglaciation (the Meltwater Spike; 15.2– 13 ka)
430 when the $S/(I+C)$ ratio reached 9 whereas the ratio remains below 8 during the Younger
431 Dryas and Holocene which is characterized by the lowest $S/(I+C)$ ratio (Fig. 9a). The results
432 highlight variations in the contribution and nature of terrigenous particles eroded and
433 transported by the Mississippi River towards the GOM interpreted as changing origin in
434 response to climate influences through the last 15 ka. Under this frame, the modifications of
435 provenance were predominantly linked to dynamics and timing of deglacial meltwater
436 discharge originating from the south margin of the LIS (such as the Meltwater Spike; Fig. 9b)
437 during the glacial periods (e.g., Licciardi et al., 1999; Flower et al., 2004; Montero-Serrano et
438 al., 2009; Sionneau et al., 2010) whereas successive migrations of the precipitation belt over

439 North America (Fig. 9c–f) resulting from the changing moisture transfer patterns became a
440 dominant process during ice-free intervals, during the Holocene (e.g., Brown et al., 1999;
441 Knox, 2000, 2003; Liu and Fearn, 2000).

442 Complementarily, we observed that the middle to late Holocene trend of the K (and
443 Ti) intensities is similar to the trend in the abundance of *G. sacculifer* (Poore et al., in press)
444 in the same core (Fig. 8e–f). However, during the early Holocene these two records show a
445 little correspondence. We interpret this lack of correlation as resulting from the impact of the
446 LIS on continental climatic variability over the early Holocene (Fig. 7a). The ice-sheet
447 probably filtered and smoothed the influence of the ITCZ and AWP on the main moisture flux
448 trajectories and migrations of the precipitation belt over North America. As a result,
449 continental processes probably responded slowly to the initial solar forcing because the LIS
450 highly impacted regional temperatures at least until 6 ka (e.g., Lovvorn et al., 2001;
451 Mayewski et al., 2004; Nordt et al., 2008). After the collapse of the LIS (~6 ka), rapid
452 atmospheric reorganization (Shuman et al., 2002) triggered rapid hydrological changes over
453 the central part of North America during the middle to late Holocene. The K (and Ti)
454 variations are synchronous with changes in the abundance of *G. sacculifer* (Fig. 8e–f) during
455 this time, suggesting that the influence of southern climate variations (such as ITCZ and
456 AWP) seems to become dominant over hydrological and erosional processes in the
457 Mississippi River watershed. These interpretations are in agreement with previous studies
458 from the GOM and the Caribbean region (e.g., Poore et al., 2003; Richey et al., 2007, 2009;
459 Wang et al., 2008).

460 To summarize, the Pigmy Basin sedimentary record suggests that the variations of the
461 Mississippi River supply are mainly controlled by the glacial processes resulting from the
462 decaying of the southern margin of LIS during the deglaciation and early Holocene, whereas
463 atmosphere–ocean interactions become the main forcing during middle to late Holocene once
464 the LIS had collapsed.

465

466 *4.5. Forcing of the atmosphere–ocean–continent oscillations—teleconnections*

467 The observed link between climatic variability (wet vs. Dry periods), atmospheric
468 configurations and clay mineral record are further evaluated using spectral analysis (Fig. 10).
469 The clay mineral assemblage variations, previously attributed to changes in the precipitation
470 belt over North America, are similar to oscillations evidenced in the Holocene glaciochemical
471 records from the GISP2 ice core (O'Brien et al., 1995; Mayewski et al., 2004). Clay mineral
472 (notably, illite+chlorite rich intervals) exhibits variations very similar with maximum sea-salt

473 sodium (ssNa) concentrations (Fig. 10a–b). Note that smectite-rich intervals in the Pigmy
474 Basin are inversely correlated to high GISP2 ssNa concentrations. The ssNa in the GISP2 ice
475 core is believed to be an indicator of storminess and sea spray in the atmosphere of the high-
476 latitude region. Thus, the variability of the Mississippi River runoff appears to be correlated
477 with changes in high-latitude atmospheric circulation. Cross-spectral analysis, using the
478 Multi-Taper (Ghil et al., 2002) and Blackman– Tukey methods (Paillard et al., 1996) between
479 the clay mineral distribution [S/(I+C) ratio] in the Pigmy Basin and GISP2 ssNa record
480 displayed the same periodicity centered around 2.5 ka (Fig. 10c). The S/(I+C) and GISP2
481 ssNa signals are coherent at 95% confidence level in the 2.5 ka frequency band with an
482 average phase of 1.05 ± 0.09 ka. The results confirm that precipitations and erosional processes
483 in the NE Mississippi River watershed have been in phase with periods of intense
484 atmospheric circulation in Greenland. Consequently, these results suggest a link between
485 large-scale atmospheric circulation changes in the high-latitude North Atlantic and the
486 hydrological and erosional changes in the North American continent.

487 The 2.5 ka periodicity also characterized ice rafted debris (IRD) occurrences in North
488 Atlantic marine sediments (Debret et al., 2007, 2009), the $\delta^{18}\text{O}$ record in GISP2 ice core
489 (Alley et al., 1997), and solar irradiance cycles (Stuiver et al., 1995). The correspondence
490 between our mineralogical data and North Atlantic paleoclimate records may be due to
491 modulation of atmospheric dynamics by solar forcing (Debret et al., 2009).

492

493 **5. Summary and conclusions**

494 Mineralogical and geochemical records of Holocene sediments from the Pigmy Basin
495 (GOM) reveal fluctuations of the Mississippi River discharge. They reflect alternations
496 between two dominant terrigenous sources (smectite vs. illite+chlorite), which are interpreted
497 as successive migrations of the main precipitation belt over North America. Holocene
498 sedimentation in the northern GOM is characterized by recurrent occurrences of smectite-rich
499 intervals associated with documented flooding episodes of the Mississippi River. Their
500 mineralogical signatures point out to specific terrigenous supply from the NW Mississippi
501 river watershed, suggesting enhanced precipitations and moisture influx from the GOM
502 toward central North America. Instead, repetitive enrichments in illite and chlorite and high K
503 intensities suggest successive eastward migrations of main precipitation belts, consistent with
504 documented evidence of increased aridity over central North America and development of
505 more humid conditions along the Atlantic margin.

506 These data provide additional information to those previously published on the North

507 American continent, Caribbean region and GOM. Their confrontation allows documenting the
508 variations of the main moisture flux trajectories over North America and of the associated
509 precipitation belt during the Holocene. Our mineralogical records evidence two main
510 atmosphere–ocean configurations that successively control moisture transfer and precipitation
511 distribution over North America throughout the Holocene:

512 (1) The northern position of the Jet Stream and southwest migration of the Bermuda
513 High promoted the influx of moisture over the central part of North America which may have
514 triggered flooding of the Mississippi River about 10–8.9, 8–6.2, 5–3.8, 2.9–1.6 and 0.8–0.3 ka
515 ago. On the opposite, the northeastern provinces experienced dry conditions.

516 (2) The southern position of the Jet Stream associated with a northeastward
517 displacement of the Bermuda High constrained the main moisture flux along the Atlantic
518 margin about 8.9–8, 6.2–5, 3.8–2.9 and 1.6–0.8 ka ago.

519 Oscillations of these two configurations promoted the repetitive occurrence of
520 drought/flooding over the northwestern Mississippi River through the Holocene. These two
521 configurations correlate with both continental and oceanic records in North America and the
522 Caribbean, and take into account the mean position of the ITCZ and AWP that modified
523 moisture balance (E–P) over the GOM and ultimately affected the hydrologic variability over
524 the North American continent. The previously discussed aspects suggest thus that during the
525 Holocene the main moisture flux trajectories and migrations of the precipitation belt over
526 North America were mainly constrained by the respective positions of the Jet Stream and
527 Bermuda High modulated by displacements of both ITCZ and AWP.

528 Spectral analysis shows a coherent common cyclicity of 2.5 ka between mineral
529 proxies from the Pigmy Basin and the Greenland sea-salt sodium record suggesting a tight
530 chronological connection between atmospheric circulation changes in the high-latitude North
531 Atlantic and the hydrological and erosional changes in the North American continent. This
532 synchronism underlines the major role played by the atmosphere compared with the ocean in
533 the moisture transfers over North America, because processes involving the ocean would have
534 induced a time lag between the respective records of the high latitudes and GOM settings.

535

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550 **References**

- 551 Aharon, P., 2003. Meltwater flooding events in the Gulf of Mexico revisited: implications for
552 rapid climate changes during the last deglaciation. *Paleoceanography* 18 (4), PA1079.
553 doi:10.1029/2002PA000840.
- 554 Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997.
555 Holocene climatic instability: a prominent, widespread event 8200 yr ago. *Geology* 25, 483–
556 486.
- 557 Bard, E., 1988. Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic
558 foraminifera: paleoceanographic implications. *Paleoceanography* 3 (6), 635–645.
- 559 Blackman, R.B., Tukey, J.W., 1958. The measurement of power spectra from the point of
560 view of communication engineering. Dover Publications. 190 pp.
- 561 Bout-Roumazeilles, V., Cortijo, E., Labeyrie, L., Debrabant, P., 1999. Clay-mineral evidence
562 of nepheloid layer contribution to the Heinrich layers in the Northwest Atlantic.
563 *Palaeogeography, Palaeoclimatology, Palaeoceanography* 146, 211–228.
- 564 Brown, P., Kennett, J.P., Ingram, B.L., 1999. Marine evidence for episodic Holocene
565 megafloods in North America and the northern Gulf of Mexico. *Paleoceanography* 14 (4),
566 498–510.
- 567 Debret, M., Bout-Roumazeilles, V., Grousset, F.E., Desmet, M., McManus, J.F., Massei, M.,
568 Sebag, D., Petit, J.R., Copard, Y., Trenteseaux, A., 2007. The origin of the 1500-year climate
569 cycles in Holocene North-Atlantic records. *Climate of the Past* 3, 569–575.
- 570 Debret, M., Sebag, D., Crosta, X., Massei, N., Petit, J.-R., Chapron, E., Bout-Roumazeilles,
571 V., 2009. Evidence from wavelet analysis for a mid-Holocene transition in global climate
572 forcing. *Quaternary Science Reviews* 28, 2675–2688.
- 573 Denniston, R.F., DuPree, M., Dorale, J.A., Asmerom, Y., Polyak, V.J., Carpenter, S.J., 2007.
574 Episodes of late Holocene aridity recorded by stalagmites from Devil's Icebox Cave, central

575 Missouri, USA. *Quaternary Research* 68, 45–52.

576 Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and
577 northern Canada. In: Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations – Extent and*
578 *Chronology, Part II*. Elsevier B.V, Amsterdam, pp. 373–424.

579 Elderfield, H., Upstill-Goddard, R., Sholkovitz, E.R., 1990. The rare earth elements in rivers,
580 estuaries and coastal seas and their significance to the composition of ocean water.
581 *Geochimica et Cosmochimica Acta* 54, 971–991.

582 Flannery, J.A., Richey, J.N., Meckler, A.N., Hollander, D.J., 2008. A 1400 Year Multi-Proxy
583 Record of Hydrologic Variability in the Gulf of Mexico: Exploring Ocean–Continent
584 Linkages During the Late Holocene. Poster Presentation, 2008 ASLO Ocean Sciences
585 Meeting. online at: [http://www.marine.usf.edu/PPBlaboratory/pages_students/](http://www.marine.usf.edu/PPBlaboratory/pages_students/flannery) flannery
586 (Revised 2009-04-01).

587 Flocks, J., Swarzenski, P., 2007. Sediment collection from Orca and Pigmy basins, Gulf of
588 Mexico, and analyses for texture and trace-metal concentrations, July 2002, PAGE 127
589 Campaign. In: Winters, W.J., Lorenson, T.D., Paull, C.K. (Eds.), *Initial Report of the*
590 *IMAGES VIII/PAGE 127 Gas Hydrate and Paleoclimate Cruise on the RV Marion Dufresne*
591 *in the Gulf of Mexico, 2–18 July 2002: U.S. Geological Survey Open-File Report 2004-1358,*
592 *one DVD.* online at <http://pubs.usgs.gov/of/2004/1358/>.

593 Flower, B.P., Hastings, D.W., Hill, H.W., Quinn, T.M., 2004. Phasing of deglacial warming
594 and laurentide ice sheet meltwater in the Gulf of Mexico. *Geology* 32, 597–600.

595 Forman, S.L., Oglesby, R., Markgraf, V., Stafford, T., 1995. Paleoclimatic significance of late
596 Quaternary eolian deposition on the Piedmont and High Plains, central United States. *Global*
597 *and Planetary Change* 11, 35–55.

598 Ghil, M., Allen, M.R., Dettinger, M.D., Ide, K., Kondrashov, D., Mann, M.E., Robertson,
599 A.W., Saunders, A., Tian, Y., Varadi, F., Yiou, P., 2002. Advanced spectral methods for
600 climatic time series. *Reviews of Geophysics* 40, 1003. doi:10.1029/2000RG000092.

601 Goldstein, S.J., Jacobsen, S.B., 1988. Rare earth elements in river waters. *Earth and Planetary*
602 *Science Letters* 89, 35–47.

603 Goman, M., Leigh, D.S., 2004. Wet early to middle Holocene conditions on the upper coastal
604 plain of North Carolina. *Quaternary Research* 61, 256–264.

605 Gromet, L.P., Dymek, R.F., Haskin, L.A., Korotev, R.L., 1984. The North American shale
606 composite: its compilation, major and trace element characteristics. *Geochimica et*
607 *Cosmochimica Acta* 48, 2469–3482.

608 Harrison, S.P., Kutzbach, J.E., Liu, Z., Bartlein, P.J., Otto-Bliesner, B., Muhs, D., Prentice,

609 I.C., Thompson, R.S., 2003. Mid-Holocene climates of the Americas: a dynamical response to
610 changed seasonality. *Climate Dynamics* 20, 663–688.

611 Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Roehl, U., 2001. Southward
612 migration of the intertropical convergence zone through the Holocene. *Science* 293, 1304–
613 1308.

614 Hodell, D.A., Curtis, J.H., Jones, G.A., Higuera-Gundy, A., Brenner, M., Binford, M.B.,
615 Dorsey, K.T., 1991. Reconstruction of the Caribbean climate change over the past 10, 500
616 years. *Nature* 352, 790–793.

617 Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck,
618 C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M.,
619 Guilderson, T.P., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, P.J.,
620 Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der
621 Plicht, J., Weyhenmeyer, C.E., 2004. Marine radiocarbon age calibration, 0–26 cal
622 kyr BP. *Radiocarbon* 46, 1059–1086.

623 Kennedy, L.M., Horn, S.P., Orvis, K.H., 2006. A 4000-yr record of fire and forest history
624 from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography,*
625 *Palaeoclimatology, Palaeoecology* 231, 271–290.

626 Knox, J.C., 2000. Sensitivity of Modern and Holocene floods to climate change. *Quaternary*
627 *Science Reviews* 19, 439–457.

628 Knox, J.C., 2003. North American palaeofloods and future floods: responses to climate
629 change. In: Gregory, K.J., Benito, G. (Eds.), *Palaeohydrology: Understanding Global Change.*
630 J. Wiley and Sons, Chichester, pp. 143–164.

631 Licciardi, J.M., Teller, J.T., Clark, P.U., 1999. Freshwater routing by the Laurentide ice sheet
632 during the last deglaciation. In: Clark, P.U., et al. (Eds.), *Mechanisms of Global Climate*
633 *Change at Millennial Time Scales*, 112. American Geophysical Union Geophysical
634 *Monograph*, pp. 177–201.

635 Liu, K.B., Fearn, M., 2000. Reconstruction of prehistoric landfall frequencies of catastrophic
636 hurricanes in Northwestern Florida from lake sediment records. *Quaternary Research* 54,
637 238–245.

638 LoDico, J.M., Flower, B.P., Quinn, T.M., 2006. Subcentennial-scale climatic and hydrologic
639 variability in the Gulf of Mexico during the early Holocene. *Paleoceanography* 21, PA3015.
640 doi:10.1029/2005PA001243.

641 Lovvorn, M.B., Frison, G.C., Tieszen, L.L., 2001. Paleoclimate and Amerindians: evidence
642 from stable isotopes and atmospheric circulation. *Proceedings of the National Academy of*

643 Sciences 98, 2485–2490.

644 Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D.,
645 Meyerson, E.A., Gasse, F., vanKreveland, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack,
646 F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability.
647 Quaternary Research 62, 243–255.

648 Meckler, A.N., Schubert, C.J., Hochuli, P.A., Plessen, B., Birgel, D., Flower, B.P., Hinrichs,
649 K.-U., Haug, G.H., 2008. Glacial to Holocene terrigenous organic matter input to sediments
650 from Orca Basin, Gulf of Mexico—a combined optical and biomarker approach. Earth and
651 Planetary Science Letters 272, 251–263.

652 Montero-Serrano, J.C., Bout-Roumazielles, V., Tribovillard, N., Sionneau, T., Riboulleau, A.,
653 Bory, A., Flower, B.P., 2009. Sedimentary evidence of deglacial megafloods in the northern
654 Gulf of Mexico (Pigmy Basin). Quaternary Science Reviews 28, 3333–3347.

655 Mueller, A.D., Islebe, G.A., Hillesheim, M.B., Grzesik, D.A., Anselmetti, F.S., Ariztegui, D.,
656 Brenner, M., Curtis, J.H., Hodell, D.A., Venz, K.A., 2009. Climate drying and associated
657 forest decline in the lowlands of northern Guatemala during the late Holocene. Quaternary
658 Research 71, 133–141.

659 Newby, P.E., Killoran, P., Waldorf, M.R., Shuman, B.N., Webb, R.S., Webb, T.I.I.I., 2000.
660 14, 000 years of sediment, vegetation, and water-level changes at the Makepeace Cedar
661 Swamp, southeastern Massachusetts. Quaternary Research 53, 352–368.

662 Nordt, L., Von Fischer, J., Tieszen, L., Tubbs, J., 2008. Coherent changes in relative C4 plant
663 productivity and climate during the late Quaternary in the North American Great Plains.
664 Quaternary Science Reviews 27, 1600–1611.

665 Nürnberg, D., Ziegler, M., Karas, C., Tiedemann, R., Schmidt, M.W., 2008. Interacting Loop
666 Current variability and Mississippi River discharge over the past 400 kyr. Earth and Planetary
667 Science Letters 272, 278–289.

668 O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., Whitlow, S.I.,
669 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. Science
670 270, 1962–1964.

671 Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh program performs time-series analysis.
672 AGU EOS Transactions 77, 379.

673 Perry, C.A., Hsu, K.J., 2000. Geophysical, archaeological, and historical evidence support a
674 solar-output model for climate change. Proceedings of the National Academy of Sciences 97,
675 12433–12438.

676 Petschick, R. 2000. MacDiff 4.2 Manual. MacDiff [Online]. Available from World Wide

677 Web: <http://www.geologie.uni-frankfurt.de/Staff/Homepages/Petschick/RainerE.html>
678 (Revised 2009-04-01).

679 Poore, R.Z., Dowsett, H.J., Verardo, S., 2003. Millennial- to century-scale variability in Gulf
680 of Mexico Holocene climate records. *Paleoceanography* 18, PA1048.
681 doi:10.1029/2002PA000868.

682 Poore, R.Z., Quinn, T.M., Verardo, S., 2004. Century-scale movement of the Atlantic
683 Intertropical Convergence Zone linked to solar variability. *Geophysical Research Letters* 31,
684 L12214. doi:10.1029/2004GL019940.

685 Poore, R.Z., Verardo, S., Caplan, J., Pavich, K., Quinn, T., in press. Planktic foraminiferal
686 relative abundance trends in the Gulf of Mexico Holocene sediments: records of climate
687 variability. In Holmes, C., (Ed.), *Gulf of Mexico, Its Origins, Waters, Biota, and Human*
688 *Impacts*. Univ Texas Press.

689 Richey, J.N., Poore, R.Z., Flower, B.P., Quinn, T.M., 2007. 1400 Yr multiproxy record of
690 climate variability from the northern Gulf of Mexico. *Geology* 35, 423–426.

691 Richey, J.N., Poore, R.Z., Flower, B.P., Hollander, D.J., Quinn, T.M., 2009. Regionally
692 coherent Little Ice Age cooling in the Atlantic Warm Pool. *Geophysical Research Letters* 36,
693 L21703. doi:10.1029/2009GL040445.

694 Richter, T.O., van der Gaast, S., Koster, B., Vaasrs, A., Gieles, R., de Stigter, H.C., de Haas,
695 H., van Weering, T.C.E., Rothwell, R.G., 2006. The Avaatech XRF Core Scanner: technical
696 description and applications to NE Atlantic sediments. In: Rothwell, R.G. (Ed.), *New*
697 *Techniques in Sediment Core Analysis: Geological Society of London, Special Publication,*
698 267, pp. 39–50.

699 Shuman, B., Bartlein, P., Logar, N., Newby, P., Webb III, T., 2002. Parallel climate and
700 vegetation responses to the early-Holocene collapse of the Laurentide Ice Sheet. *Quaternary*
701 *Science Reviews* 21, 1793–1805.

702 Shuman, B., Bartlein, P., Webb III, T., 2005. The magnitudes of millennial- and orbital scale
703 climatic change in eastern North America during the Late Quaternary. *Quaternary Science*
704 *Reviews* 24, 2194–2206.

705 Sionneau, T., 2008. *Transferts Continent – Océan : Enregistrement du dernier cycle*
706 *climatique par les sédiments terrigènes du Golfe du Mexique*. PhD thesis, Université Lille 1.
707 377 p. online at <http://tel.archives-ouvertes.fr/tel-00366377/fr/>.

708 Sionneau, T., Bout-Roumazeilles, V., Biscaye, P.E., van Vliet-Lanoë, B., Bory, A., 2008.
709 Clay-mineral distributions in and around Mississippi River watershed and Northern Gulf of
710 Mexico: sources and transport patterns. *Quaternary Science Reviews* 27, 1740–1751.

711 Sionneau, T., Bout-Roumzeilles, V., Flower, B.P., Bory, A., Tribovillard, N., Kissel, C., Van
712 Vliet-Lanoë, B., Montero-Serrano, J.C., 2010. Provenance of freshwater pulses in the Gulf of
713 Mexico during the last deglaciation. *Quaternary Research* 74, 235–245.

714 Stuiver, M., Reimer, P.J., 1993. Extended 14C data-base and revised calib 3.0 14C age
715 calibration program. *Radiocarbon* 35, 215–230.

716 Stuiver, M., Grootes, P.M., Braziunas, T.F., 1995. The GISP2 #18O climate record of the past
717 16, 500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* 44, 341–
718 354.

719 Thompson, D.J., 1982. Spectrum estimation and harmonic analysis. *Proceedings of the IEEE*
720 70, 1055–1098.

721 Tribovillard, N., Algeo, T., Lyons, T.W., Riboulleau, A., 2006. Trace metals as paleoredox
722 and paleoproductivity proxies: an update. *Chemical Geology* 232, 12–32.

723 Wang, C., Enfield, D.B., 2001. The tropical Western Hemisphere warm pool. *Geophysical*
724 *Research Letters* 28, 1635–1638.

725 Wang, C., Lee, S.-K., Enfield, D.B., 2008. Climate response to anomalously large and small
726 Atlantic warm pools during the summer. *Journal of Climate* 21, 2437–2450.

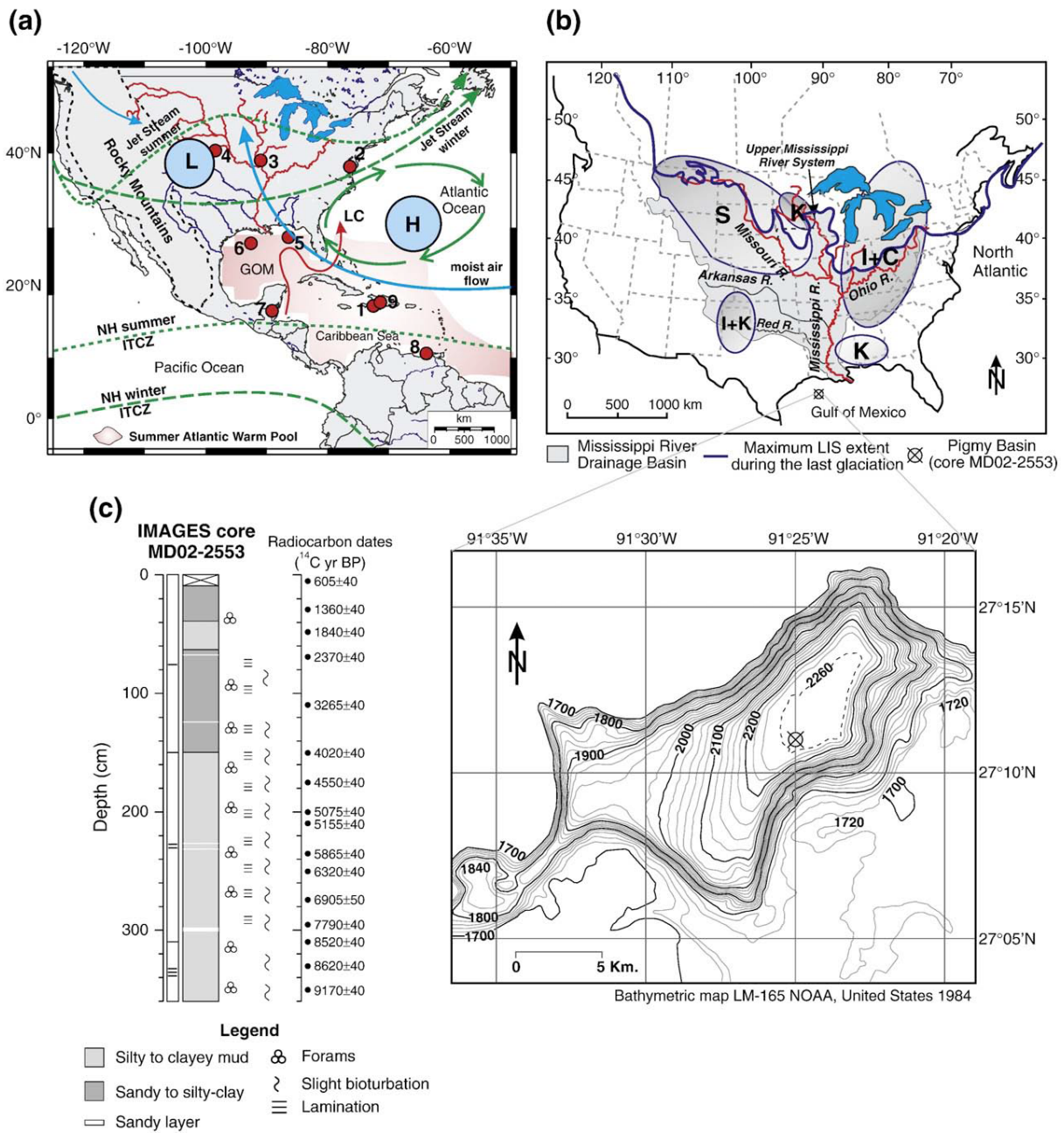
727 Wedepohl, K.H., 1971. Environmental influences on the chemical composition of shales and
728 clays. In: Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C. (Eds.), *Physics and Chemistry of*
729 *the Earth*. Pergamon, Oxford, pp. 305–333.

730 Wedepohl, K.H., 1991. The composition of the upper Earth's crust and the natural cycles of
731 selected metals. In: Merian, E. (Ed.), *Metals and Their Compounds in the Environment*.
732 VCH-Verlagsgesellschaft, Weinheim, pp. 3–17.

733 Willard, D.A., Bernhardt, C.E., Korejwo, D.A., Meyers, S.R., 2005. Impact of millennial
734 scale Holocene climate variability on eastern North American terrestrial ecosystems: pollen-
735 based climatic reconstruction. *Global and Planetary Change* 47, 17–35.

736 Ziegler, M., Nürnberg, D., Karas, C., Tiedemann, R., Lourens, L.J., 2008. Persistent summer
737 expansion of the Atlantic Warm Pool during glacial abrupt cold events. *Nature Geoscience* 1
738 (9), 601–605.

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741

742 Fig. 1. (a) Map showing the location of selected localities discussed in this study, generalized

743 position of the Intertropical Convergence Zone (ITCZ) for Northern Hemisphere (NH) winter

744 and summer [adapted from Ziegler et al. (2008)], the summer position of the Atlantic Warm

745 Pool [adapted from Wang and Enfield (2001)], the mean configuration of the Jet Stream

746 during winter and summer regimes (adapted from Knox, 2000, 2003), and the mean summer

747 position of the Bermuda High and the Thermal Low relative to North America [adapted from

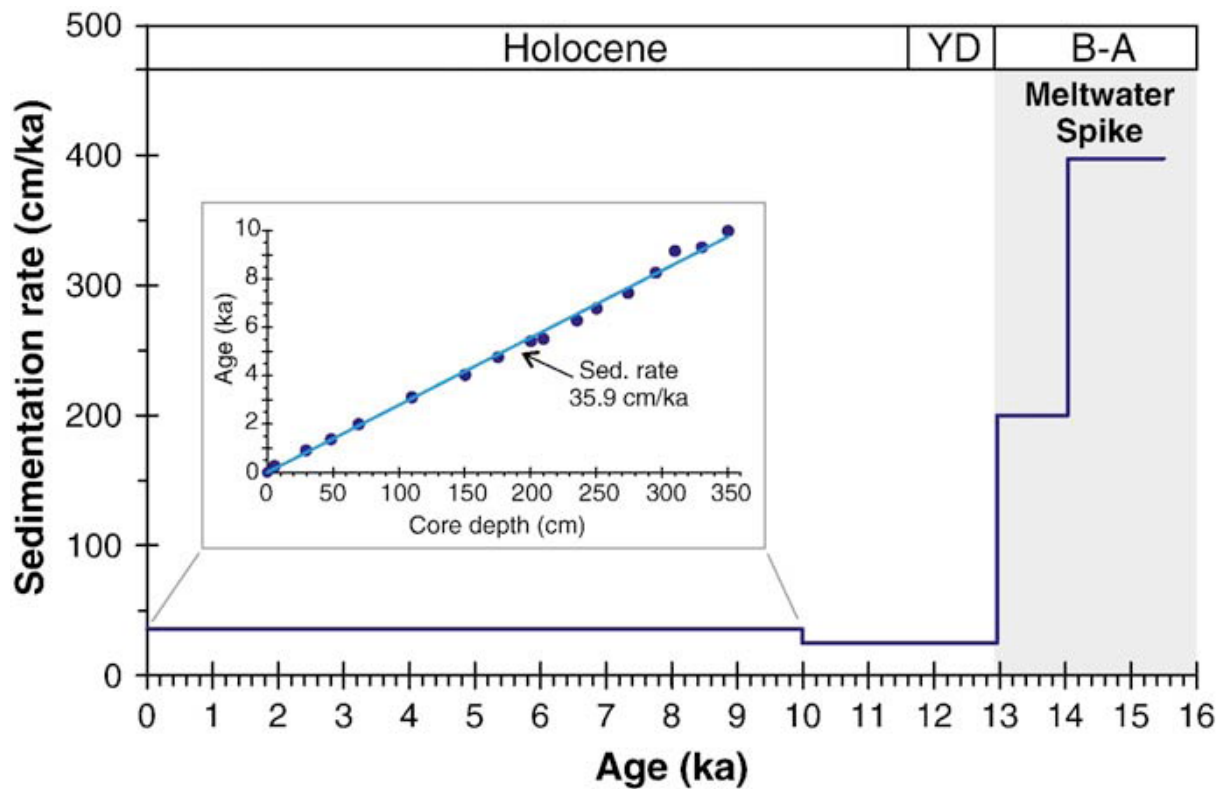
748 Forman et al. (1995) and Liu and Fearn (2000)]. (b) The Mississippi River watershed showing

749 the main continental clay mineral provinces over the United States (Sionneau et al., 2008) and

750 the Last Glacial Maximum extent of the Laurentide Ice Sheet (Dyke, 2004). The letters S, I, C

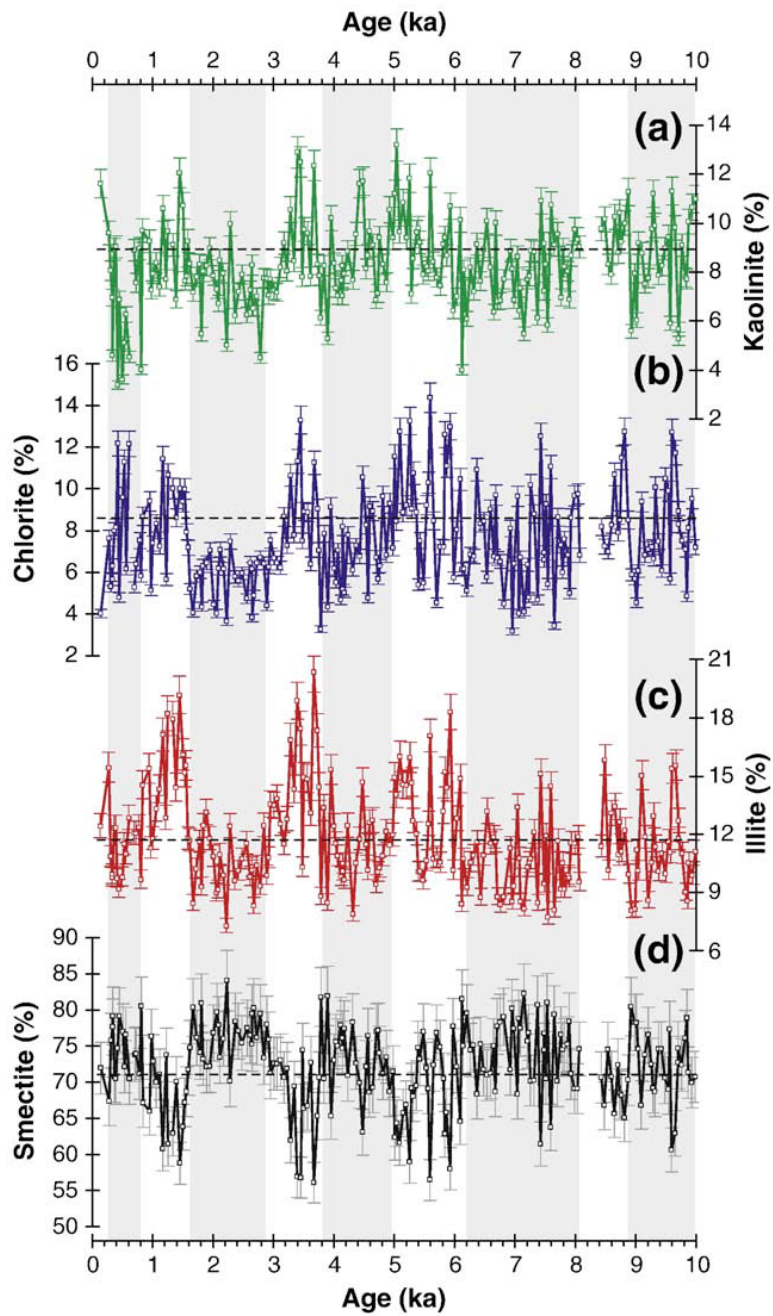
751 and K (standing for smectite, illite, chlorite and kaolinite, respectively) indicate areas where
752 the bedrock/soils contain a clay mineral assemblage markedly dominated by one clay species.
753 Note that the Mississippi River receives main discharges from the Missouri (NW)+Ohio (NE)
754 rivers system, which drains almost half of the conterminous USA (e.g., Sionneau et al., 2008).
755 GOM: Gulf of Mexico, LC: Loop Current. Numbers at each site are: (1) Lake Miragoane,
756 Haiti; (2) Chesapeake Bay, northeastern of the North America; (3) Devil's Icebox Cave,
757 central Missouri; (4) North American Great Plains, (5) DeSoto Canyon, northeastern GOM;
758 (6) Pigmy and Oraca Basin, northern GOM; (7) Lake Petén Itzá, northern Guatemala; (8)
759 Cariaco Basin, offshore northern Venezuela; (9) Cordillera Central, Dominican Republic. (c)
760 Lithological log of core MD02-2553 between 0 and 360 cm showing the sedimentological
761 characteristics and radiocarbon ages (Poore et al., in press).

762



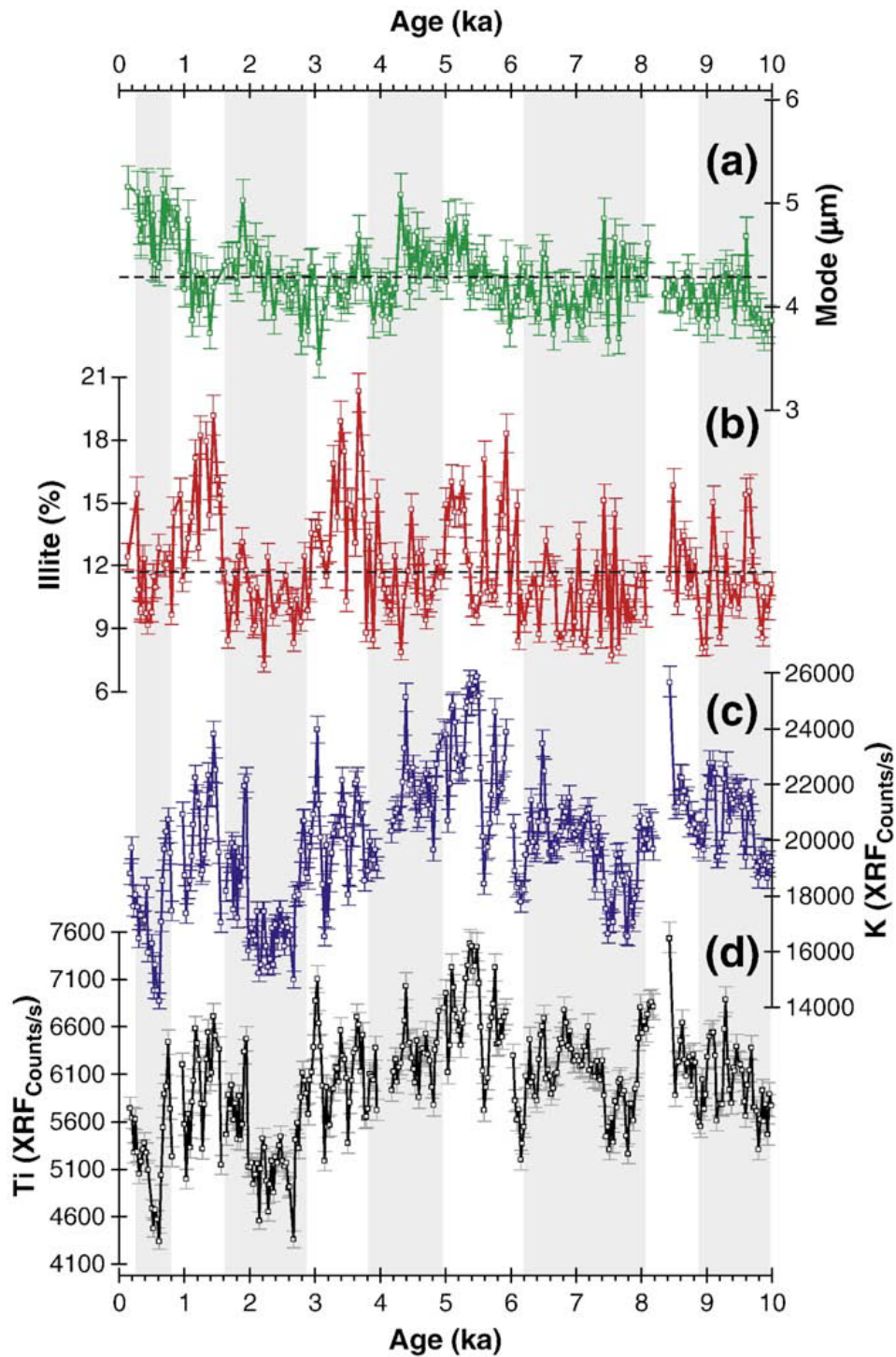
763

764 Fig. 2. Sedimentation rates of the Pigmy Basin (cores MD02-2553) in the GOM during the
 765 Glacial-Holocene transition. The Younger Dryas (YD) from 12.9 to 11.6 ka and Bølling-
 766 Allerød warming (B-A) from 15.4 to 12.9 ka are indicated. Data from 10 to 15.2 ka from
 767 Montero-Serrano et al. (2009). Inset in left shows age model for core MD02-2553 based on
 768 16 AMS 14C dates from mixed planktic foraminifers (Poore et al., in press), converted to
 769 calendar ages (Table 1). Depth in centimeters was converted to calendar age by linear
 770 interpolation (1 ka=1000 cal yr BP).



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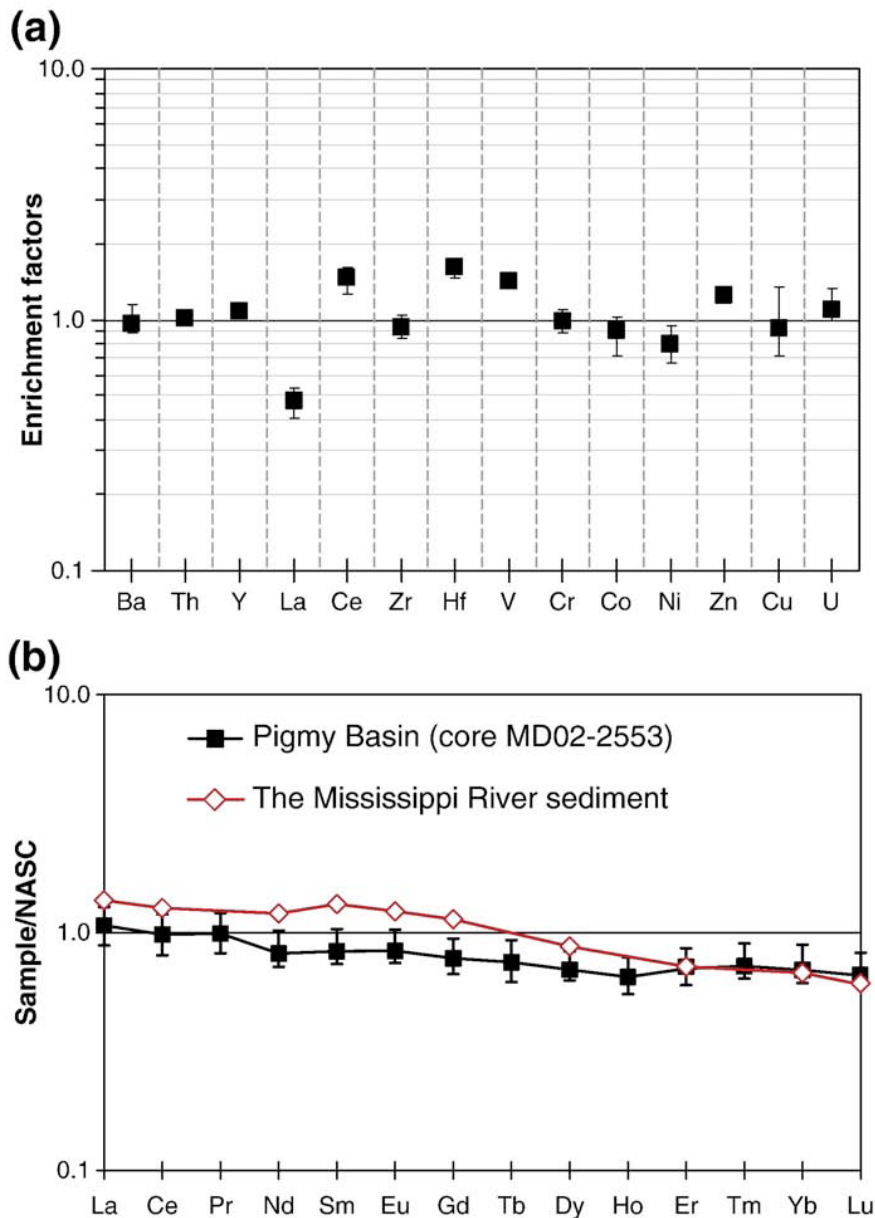
772 Fig. 3. Clay mineral assemblages from the Pigmy Basin (core MD02-2553). The horizontal
 773 dotted lines indicate the mean concentrations for each clay mineral. The smectite-rich
 774 intervals are indicated in gray bands. The semi-quantitative evaluation of each clay mineral
 775 has an accuracy of ~5%.



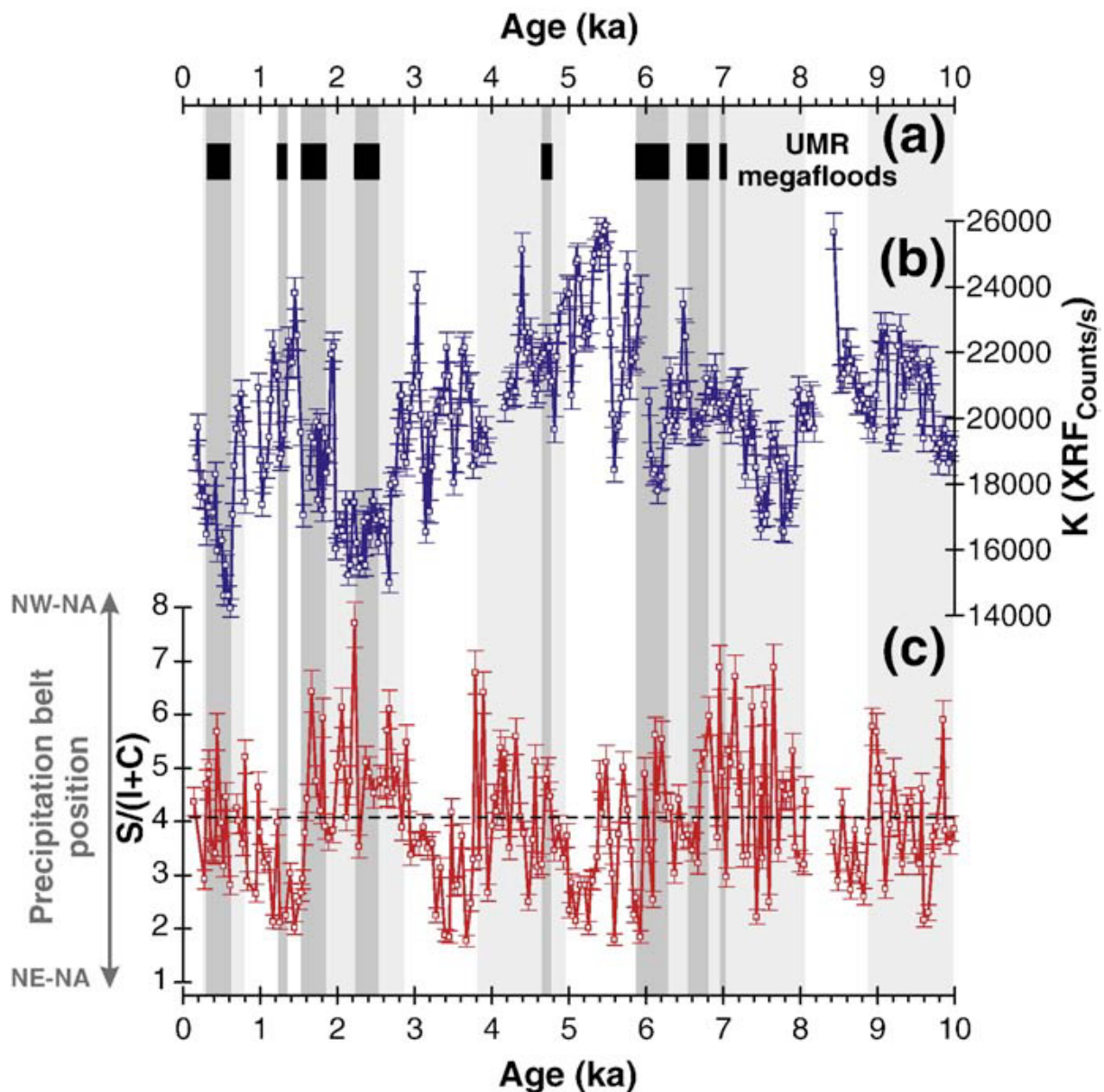
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777 Fig. 4. Comparison of sedimentological and geochemical records from the Pigmy Basin (core
 778 MD02-2553). (a) Grain-size mode distributions (μm), (b) illite (%), and (c–d) K and Ti
 779 intensities in counts per second. The horizontal dotted lines indicate the mean concentrations
 780 for the grain-size mode and illite. Clay mineral, grain-size and XRF core scanner analyses
 781 have accuracy better than 5%, 4% and 2%, respectively. The smectite-rich intervals are
 782 indicated in gray bands.

783



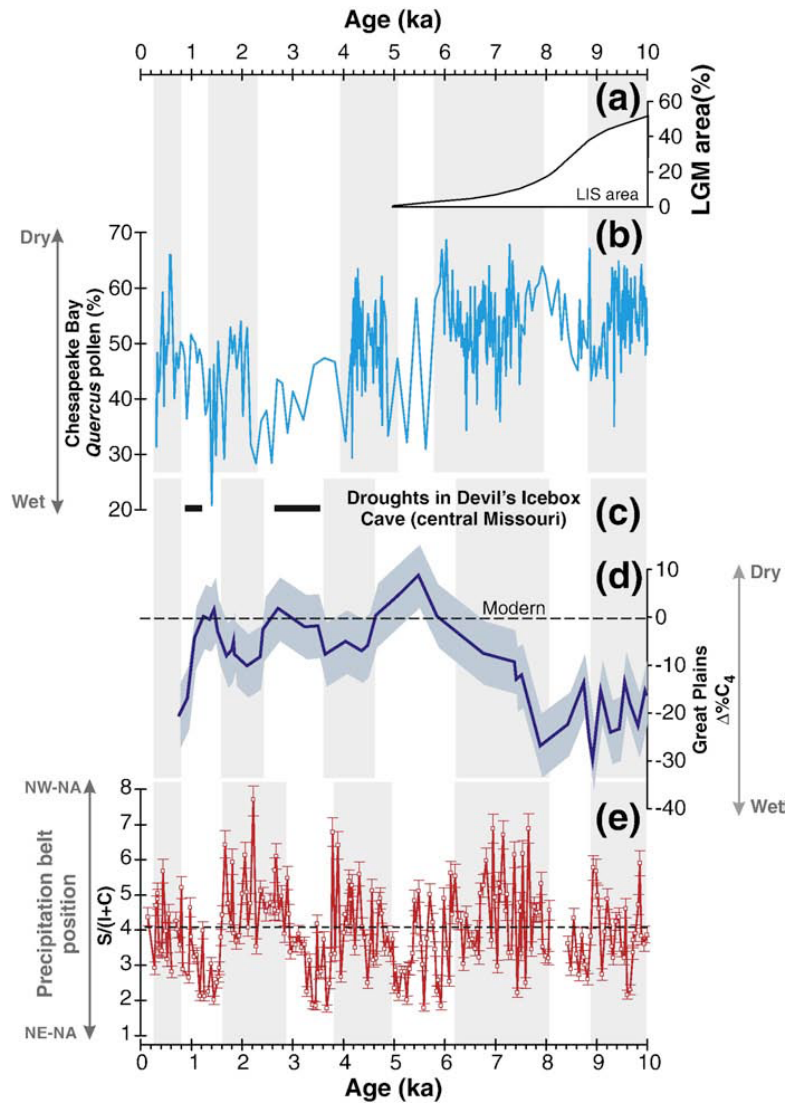
784
 785 Fig. 5. (a) Comparisons of the enrichment factor of selected trace metals of core MD02- 2553
 786 (Pigmy Basin). The extent line of the boxes corresponds to the range of values (min-max)
 787 and the boxes to the average value. The horizontal line EF=1 indicates the value for which
 788 there is no enrichment/depletion with regards to average shale composition. (b) Comparison
 789 of REE patterns between the averages of the Pigmy Basin and Mississippi River sediments
 790 (Goldstein and Jacobsen, 1988; Elderfield et al., 1990). NASC values by Gromet et al. (1984)
 791 are used for normalization. The analytical accuracy and precision were found to be better than
 792 5–10% for trace element and 5% for REE, as checked by international standards and analysis
 793 of replicate samples.
 794



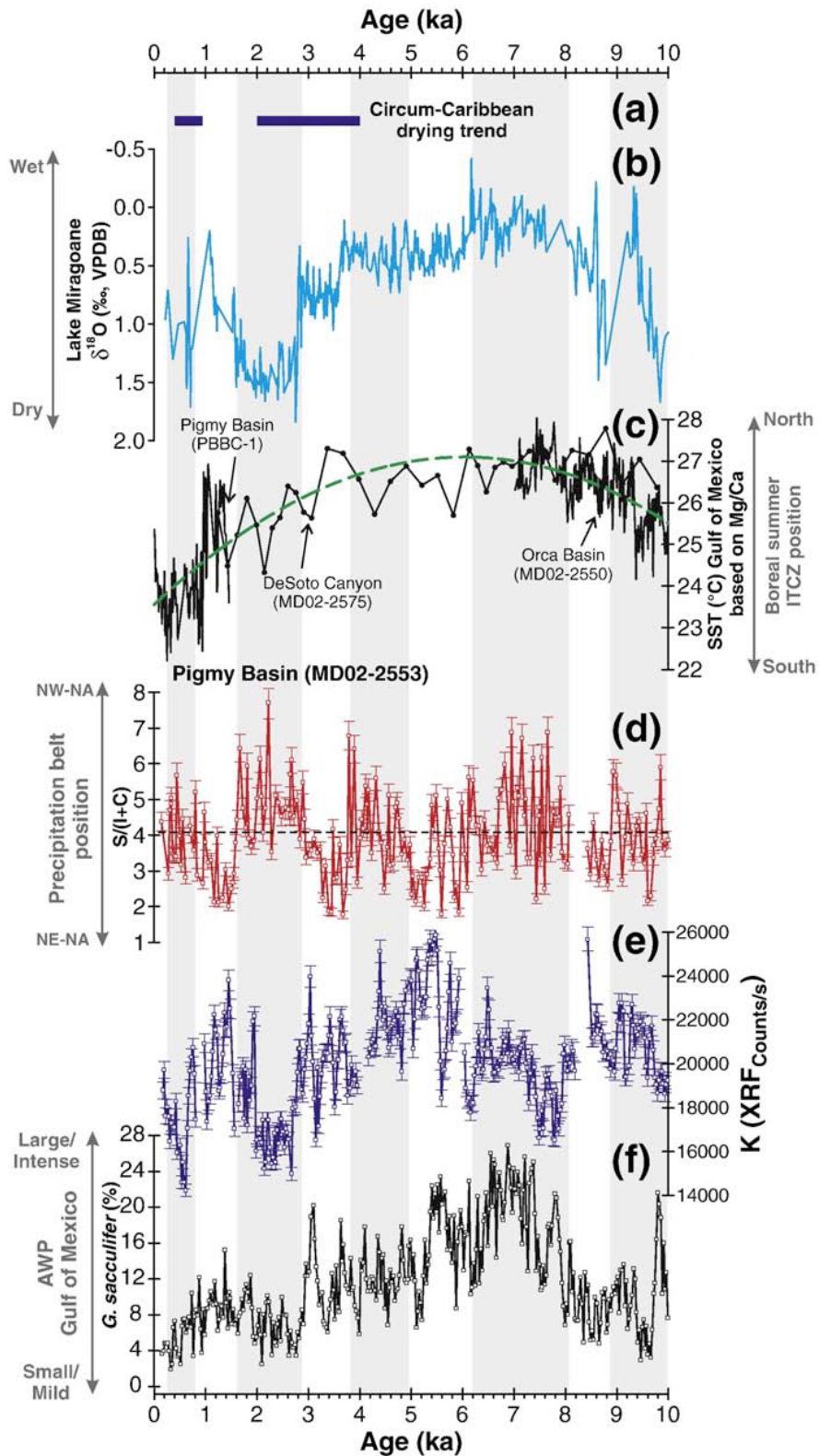
795

796 Fig. 6. Comparison of the mineralogical [S/(I+C) ratio] and geochemical records (K
 797 intensities) of Holocene sediments from the Pigmy Basin (GOM) with the Upper Mississippi
 798 River (UMR) channel megafloods episodes (Knox, 2003) from the central part of North
 799 America (dark gray bands). Based on a simple error propagation, error on S/(I+C) ratio is
 800 about 6%. XRF core scanner analyses have accuracy better than 4%. The smectite-rich
 801 intervals are indicated in light gray bands.

802



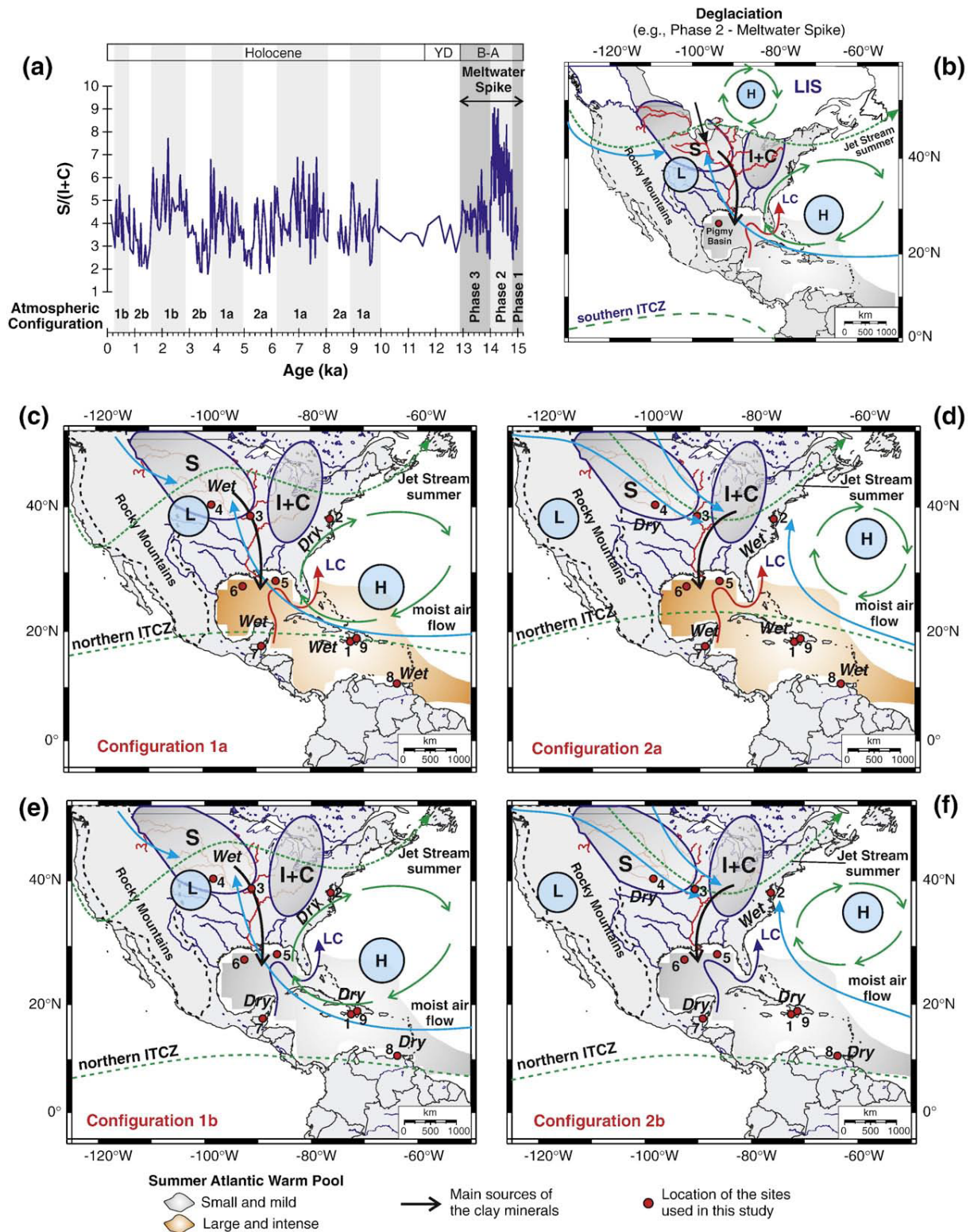
803
 804 Fig. 7. Comparison of the mineralogical signature recorded in the Pigmy Basin (core MD02-
 805 2553) with the North American climate records: (a) the area of the Laurentide ice sheet (LIS)
 806 as a fraction of the area during the last glacial maximum (LGM), adapted from Shuman et al.
 807 (2005); (b) palynological records from Chesapeake Bay, northeastern USA (Willard et al.,
 808 2005); (c) episodes of late Holocene aridity (based in positive $\delta^{13}\text{C}$ excursions) recorded by
 809 stalagmites from Devil's Icebox Cave, central Missouri, USA (Denniston et al., 2007); (d)
 810 isotopic analysis of soil organic carbon ($\Delta\text{‰C}_4$) in the North American Great Plains (Nordt et
 811 al., 2008). $\Delta\text{‰C}_4$ is derived from the equation $\Delta\delta^{13}\text{C}_{\text{C}_4} = \delta^{13}\text{C}_{\text{C}_4 \text{ buried soil}} - \delta^{13}\text{C}_{\text{C}_4 \text{ modern latitudinal}}$
 812 (see Nordt et al., 2008 for procedural details). (e) Smectite/(Illite+Chlorite) ratio from the
 813 core MD02-2553. Based on a simple error propagation, error on S/(I+C) ratio is about 6%.
 814 The smectite-rich intervals are indicated in gray bands. The differences in timing and phasing
 815 of the smectite-rich intervals in the GOM sediments and continental climatic
 816 interpretations most likely reflect uncertainties in the individual chronologies.
 817



818

819 Fig. 8. Comparison of the multi-proxy record from the Pigmy Basin (core MD02-2553) with
 820 the Caribbean and GOM climate records: (a) previous interpretations of paleoclimate from the
 821 circum-Caribbean region. The Petén Itzá Lake (northern Guatemala; Mueller et al., 2009),
 822 Cordillera Central (Dominican Republic; Kennedy et al., 2006) and Cariaco Basin (offshore
 823 northern Venezuela; Haug et al., 2001); (b) oxygen isotope data from Lake Miragoane (Haiti;

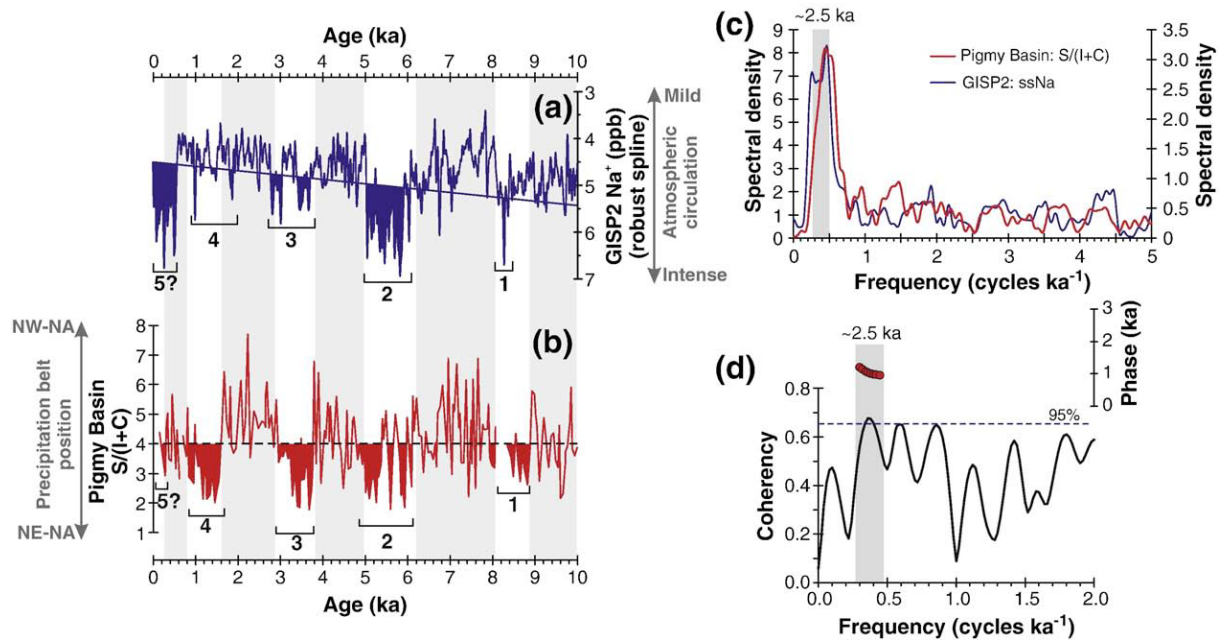
824 Hodell et al., 1991). Original radiocarbon scale was converted to calendar year scale using
825 CALIB 5.0.2 (Stuiver and Reimer, 1993); (c) composite records of sea-surface temperature
826 (SST, °C) from GOM; core MD02-2550 from LoDico et al. (2006), core MD02-275 from
827 Nürnberg et al. (2008) and core PBBC-1 from Richey et al. (2007); (d–e) mineralogical and
828 geochemical proxies from the core MD02-2553; (f) relative abundance of the warm water
829 species *G. sacculifer* in the northern GOM (core MD02-2553; Poore et al., in press).
830 Variations in the *G. sacculifer* abundance in the GOM sediments are related to the influx of
831 Caribbean surface waters into the GOM (expansion of the Atlantic Warm Pool) and the
832 average position of the ITCZ (Poore et al., 2004). Based on a simple error propagation, error
833 on S/(I+C) ratio is about 6%. XRF core scanner analyses have accuracy better than 4%. The
834 smectite-rich intervals are indicated in gray bands.



835

836 Fig. 9. (a) Clay mineral variations [$S/(I+C)$ ratio] in the Pigmy Basin sediments during the
 837 Glacial-Holocene transition. The smectite-rich intervals are indicated in light gray bands.
 838 Dark gray bands denote intervals of the mixed provenance (smectite and illite+chlorite) of
 839 detrital particles during the deglaciation. Based on a simple error propagation, error on
 840 $S/(I+C)$ ratio is about 6%. (b) Extent of the southern margin of Laurentide Ice Sheet during

841 the last deglaciation (~14.7 ka; Dyke, 2004), showing a dominant origin from NW North
842 America for detrital particles delivered to the GOM via the Mississippi River (Montero
843 Serrano et al., 2009). (c–f) Generalized reconstructions of regional atmospheric circulation
844 patterns during the Holocene summer in the middle-latitude North America and their
845 paleoclimatic implications. (c and e) Configurations during the predominant wet periods in
846 central North America (10–8.9, 8–6.2, 5–3.8, 2.9–1.6, 0.8–0.3 ka). (d and f) Configurations
847 during predominant dry periods in central North America (8.9–8, 6.2–5, 3.8–2.9 and 1.6–0.8
848 ka). The Jet Streams denote the approximate boundaries of air masses from the tropical,
849 pacific and polar-source regions and locations of the areas with the main moisture transfers
850 over the North American continent (adapted from Knox, 2000, 2003). The mean summer
851 position of the Bermuda High and the Thermal Low relative to North America are modified
852 from Forman et al. (1995) and Liu and Fearn (2000). Note that the mean latitudinal shifts of
853 the Intertropical Convergence Zone (ITCZ) and meridional extension of the Atlantic Warm
854 Pool (AWP) through the Holocene are monitored using paleoclimate records from the circum-
855 Caribbean region and the northern GOM (Fig. 8a–c, f). Red and dark shade represents a more
856 and less established AWP. Numbers at each site are as in Fig. 1a.



858

859 Fig. 10. (a) Holocene glaciochemical record from the GISP2 ice (O'Brien et al., 1995;
 860 Mayewski et al., 2004) compared with (b) clay mineral distribution [S/(I+C) ratio] from the
 861 Pigmy Basin. Numbers in (a) and (b) represent tentative correlations between the
 862 illite+chlorite-rich intervals of Pigmy sediments and intervals with high concentrations of
 863 GISP2 sea-salt sodium (ssNa; shaded values from O'Brien et al., 1995). NW-NA:
 864 northwestern North America, NE-NA: northeastern North America. Spectral analysis: (c)
 865 Multi-Taper spectral analysis of the S/(I+C) ratio and GISP2 sea-salt sodium (ssNa). (d)
 866 Cross-spectral analysis, based on the Blackman–Tukey method, between the S/(I+C) ratio and
 867 GISP2 ssNa record. Lower panel: coherency spectrum. Upper panel: phase. All periodicities
 868 significant above 95% are labeled.

869 Table 1

870 Radiocarbon ages for core MD02-2553 (Poore et al., in press).

| Core depth (cm) | Species | ¹⁴ C AMS age (ka) | ¹⁴ C Error (± yr) | Calibrated age (median, ka BP) | Calibrated error (± yr, 1 sigma) |
|-----------------|-----------------------------|------------------------------|------------------------------|--------------------------------|----------------------------------|
| 0 | Mixed planktic foraminifers | 0 | | 0 | 0 |
| 5.5 | | 0.605 | 40 | 0.260 | 37 |
| 29.5 | | 1.360 | 40 | 0.907 | 49 |
| 48.5 | | 1.840 | 40 | 1.370 | 54 |
| 69.5 | | 2.370 | 40 | 1.993 | 60 |
| 110.0 | | 3.265 | 40 | 3.102 | 71 |
| 150.5 | | 4.020 | 40 | 4.029 | 65 |
| 175.5 | | 4.550 | 40 | 4.765 | 57 |
| 200.5 | | 5.075 | 40 | 5.428 | 50 |
| 210.0 | | 5.155 | 40 | 5.523 | 43 |
| 235.5 | | 5.865 | 40 | 6.284 | 47 |
| 250.5 | | 6.320 | 40 | 6.783 | 58 |
| 274.5 | | 6.905 | 50 | 7.420 | 51 |
| 295.5 | | 7.790 | 40 | 8.259 | 52 |
| 310.0 | | 8.520 | 40 | 9.157 | 72 |
| 330.5 | | 8.620 | 40 | 9.307 | 65 |
| 350.5 | | 9.170 | 40 | 9.989 | 89 |

871