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15

16 **Abstract**

17 The right-lateral strike slip Boconó Fault (Mérida Andes, northern Venezuela)  
18 accommodates an important part of the South-American Plate northern transform boundary.  
19 Along its central portion, preserved post-LMG lake fills are intersected by two surface-  
20 reaching active traces which could be trenched just beside. Outcropping and cored lacustrine  
21 sedimentary archives are combined with trench data in order to achieve a Holocene  
22 paleoseismicity record for a 7 km-long segment. For lakes sediments, several types of  
23 sedimentary “events” were taken into account as co-seismic: mass wasting on deltaic foreset,  
24 liquefaction and slumping, reflected tsunami effects, re-suspension, abrupt change in  
25 sedimentary dynamics and sources, abrupt emptying and lake surface changes. Time  
26 coincidences between two lacustrine archives and two trenches can be proposed for the last 10  
27 kyr BP. Among a total of 24 events, 13 events are detected in two sites, 3 events in 3 sites. 9  
28 possible correlations concern separate traces while 4 concern the same trace; a relay between  
29 the activity of the two traces is also deduced. This combination of surveys both reinforces and  
30 completes the trenches results, leading to a better knowledge of local to regional seismic  
31 hazard. Nevertheless, the total information results probably incomplete and/or biased. The co-  
32 seismic origin of lacustrine fills disturbances evidenced but the associated archive is  
33 incomplete and/or biased due to: changing recording potential through time, possible impacts  
34 by strong distant earthquakes. Trenches data appear to fill lacustrine “gaps” but with a number

35 of events possibly overestimated if all ruptures and associated  $^{14}\text{C}$  data are considered as  
36 representing separated earthquakes.

37

38 **Key-words:** paleosismicity, lake sediments, trenches, Last Glacial Maximum, Holocene,  
39 Mérida Andes, Boconó Fault.

40

#### 41 **1. Introduction:**

42 Since pioneer investigations and discoveries on sedimentary recording of seismic  
43 shocks (e.g. Sims, 1973; Adams, 1990), “subaqueous” paleosismology widely developed both  
44 for marine and for lacustrine accumulations. Meanwhile, paleoseismology based on field  
45 survey, which began several decades before, largely benefited from the development and  
46 improvement of trenches analyses (*in* McCalpin and Nelson, 2009; Weldon et al, 2009).  
47 Beside, major active faults, as the Dead Sea Fault and the North-Anatolian Fault, have been  
48 surveyed through their coeval sedimentation (e.g. Marco and Agnon, 1995; McHugh et al.,  
49 2006, 2014; Gorsline et al., 2000; Beck et al., 2007, 2015). For lacustrine or marine  
50 sediments, the most frequent inferred processes leading to earthquake recording belong to  
51 three groups: 1) *in situ* disturbances related to rheological contrast between successive layers  
52 (e.g. Moretti et al., 1999; Rodriguez-Pascua et al, 2003; Wetzler et al, 2005), 2) simple gravity  
53 reworking (turbidites, Mass Transport Deposits/MTDs; e.g. Strasser et al., 2006; Goldfinger  
54 et al., 20012), and, 3) gravity reworking with additional coeval specific particles re-settling  
55 (combination with tsunami/seiche effect) (e.g. Chapron et al., 1999; Beck, 2009; Beck et al.,  
56 2007; McHugh et al., 2011; Campos et al., 2013). For small-sized lakes, possible impacts on  
57 watershed and basin geometry may be recorded through sedimentary feeding and/or  
58 depositional dynamic (e.g. Carrillo et al., 2008; Avşar et al., 2015; Aguilar et al., 2015).

59 To our knowledge, the combination of trench data and lacustrine sedimentary archives,  
60 both related to the same active seismogenic fault, has scarcely been attempted. The here-  
61 presented work concerns a favourable site for such combined approaches: the central part of  
62 the Mérida Andes (North-western Venezuela) crosscut by the Boconó Fault. Within the frame  
63 of the same research program, we could achieve: outcrop analyses, lake sediments coring, and  
64 trenching. The present article presents the last phase of these investigations: an attempt to  
65 integrate trenches results published in 1999 and 2008, and lacustrine archives data published  
66 in 2006 and 2008. The here-discussed data combined these results with new additional  
67 investigations dedicated: 1) to lacustrine sediments depositional processes and chronology, 2)  
68 to deep-seated gravitational slope deformations bounding the Boconó Fault (Audemard et al.,

69 2010), 3) to the chronology of the last deglaciation using cosmogenic isotopes (Carcaillet et  
70 al., 2013). Thus, for the following, we present as new data: a final interpretation of  
71 sedimentological investigations, including structural positions, and a completed chronology of  
72 all compared events.

73

## 74 **2. Investigated area: the central portion of the Boconó Fault**

### 75 **2.1. Geodynamic and tectonic setting**

76 The southern limit of the Caribbean Plate - the northern limit of the South-America  
77 Plate - is a complex transform system with some convergence component (Fig. 1-B;  
78 simplified from Stéphan et al., 1990; Audemard et al., 2000; DeMets et al., 2000; Pérez et al.,  
79 2001; Weber et al., 2001; Symithe et al., 2015). In north-western Venezuela, part of the 2  
80 cm/yr global displacement is partitioned into major faults bounding the so-called “Santa  
81 Marta Triangular Block” or “Maracaibo Triangular Block”. The Mérida Andes (Fig. 1-A)  
82 represent the active relieves accommodating part of this relative plate displacement and  
83 associated stress field; they culminate at 4998 m a.s.l.. The Boconó Fault - dextral strike slip -  
84 is roughly following the backbone of this SW-NE trending chain. In a review of available  
85 Global Navigation Satellite System surveys data applied to northern Venezuela, Reinoza et al.  
86 (2015) mention a 9-to-11 mm/y horizontal slip rate and a 1 mm/y convergence orthogonal to  
87 the Mérida Andes. Previous estimations of the slip rate along the Boconó Fault, based on field  
88 surveys, concluded to a 7-to-10 mm/y (Audemard et al., 1999). More recent investigations  
89 combining  $^{10}\text{Be}$  and high resolution satellite imagery concluded to similar values (up to 11,2  
90 mm/yr) for the north-eastern strand (Pousse-Beltran et al., 2017).

91 As other major strike slip faults in northern Venezuela (El Pilar F., San Sebastian F.,  
92 Fig. 1-B), the Boconó Fault was soon recognized by Rod (1956) as responsible for large  
93 historical earthquakes. Later works (Cluff and Hansen, 1969; Aggarwal, 1983; *in* Audemard  
94 et al. (2010)) attributed several major events (e.g. 1610, 1812, 1644, 1875, 1950) to the  
95 Boconó Fault activity; 6.5 to 7.4 Mw magnitudes have been estimated (Palme et al., 2005, and  
96 *in* Audemard et al. (2008)). More recent paleoseismic investigations through trenching, and  
97 seismotectonic approaches, permitted to precise the distribution of major earthquakes along  
98 different segments of the fault, and, by mean, to better estimate seismic hazards (Audemard,  
99 1997, 2003, 2005; Pousse-Beltran et al., 2018). Results from the trenches performed in the  
100 investigated area (white rectangle on Fig. 1B) will be summarized in § 4. The two concerned  
101 trenches (Morro de los Hoyos and Mesa del Caballo; Audemard et al., 1999, 2008) are  
102 precisely located on Figure 2.

103 In the investigated area, the highest relieves consist of Late Proterozoic igneous and  
104 metamorphic rocks (orthogneiss, paragneiss, amphibolites, granitic pegmatites, aplites). The  
105 Boconó Fault crosscuts this basement and also the Late Quaternary sediments developed  
106 during the last climatic cycles, and directly resting on the Precambrian formations. Gneiss and  
107 pegmatite fragments are the main components of Pleistocene coarse deposits, and especially  
108 of the well-preserved morainic systems related to the last glaciation.

109

## 110 **2.2. Imprint of the last climatic cycles in central Mérida Andes**

111 Although located in tropical zone, due to the altitude of their central part, the Mérida  
112 Andes, and especially the studied area, underwent a neat impact of the last glacio-eustatic  
113 cycles. Several well-preserved morainic systems (Fig. 2) have been attributed to the Last  
114 Glacial Maximum (equivalent for MIS2) here called “Mérida Glaciation” (Schubert, 1974;  
115 Salgado-Labouriau and Schubert, 1976). Glacigenic sediments and erosion surfaces  
116 developed above 2500 m with associated moraine-dammed lacustrine fills and peat-bogs. The  
117 different LGM and post-LGM formations have been the focus of paleoecological and  
118 paleoclimatic reconstructions (Salgado-Labouriau et al, 1977, 1992; Bradley et al., 1985;  
119 Weingarten et al., 1990; Rull, 1996; Mahaney et al., 1997, 2000; Stansell et al., 2005). Beside  
120 the well-defined LGM remnants, few tills bodies and organic-rich lacustrine sediments have  
121 been attributed to a pre-LGM glacial stage, based on their relationships with the LGM  
122 glacigenic sets and  $^{14}\text{C}$  dating (Rull, 1996; Mahaney et al., 1997, 2000). More recent  
123 cosmogenic isotopes analyses permitted to estimate erosion rates (Wesnousky et al., 2012)  
124 and to precise the pattern and velocity of the post-LGM glacial retreat (Angel et al., 2013;  
125 Carcaillet et al., 2013). The impact of the Little Ice Age has also been tested in the studied  
126 area (Polissar et al., 2006). For the here-presented area, a set of 16  $^{10}\text{Be}$  measurements were  
127 performed: on morainic complex crests boulders, and on free striated surfaces (Angel et al.,  
128 2013; Carcaillet et al., 2013). The maximum advance is dated back to 18 kyr BP for the  
129 highest site (Mucubají), which is in agreement with  $^{14}\text{C}$  ages previously found for associated  
130 lacustrine sediments (Carrillo et al, 2008).

131

## 132 **2.3. The Boconó Fault across the post-LGM lacustrine basins**

133 Beside their high paleoclimatic interest, the Mérida Andes' glacigenic and post-glacial  
134 sedimentary bodies were soon used as precious tectonic benchmarks to quantify the Boconó  
135 Fault activity (Schubert, 1982). Most of them are crosscut by surface-reaching active traces,  
136 and horizontally displaced (Fig. 2). We focused our work on two of these morainic systems

137 and their associated lacustrine sedimentary fills: the Los Zerpa site and the Mucubají site. A  
138 major south-eastern active trace and a less visible north-western trace were chosen for  
139 structural and paleoseismic analyses in trenches (Audemard et al., 1999, 2008). The south-  
140 eastern active trace just bounds the Los Zerpa lacustrine sediments (Fig. 3, section AA') while  
141 it crosscuts Lake Mucubají (locally named "Laguna de Mucubají") (Fig. 3, section BB'). A  
142 minor transtensional component also characterizes the studied portion of the Boconó Fault,  
143 indicated by: normal ruptures within moraines, "micro pullapart" depressions or sagponds,  
144 and low angle NE-dipping slickendides. In the Los Zerpa/Mucubají área, a large north-  
145 westwards landslide displaces the whole Late Quaternary pile on the southeastern side of the  
146 fault (Audemard et al., 2010). This gravitational deformation is also related to the local  
147 transtensional component and inferred to be activated by strongest earthquakes (Audemard et  
148 al., 2010; and this work).

149

### 150 **3. Summary and interpretation of paleoseismic results deduced from lacustrine** 151 **sedimentary archives**

152 Our investigations for subaqueous paleoseismic purpose were dedicated to the Los Zerpa  
153 and the Mucubají lacustrine sediments accumulated within morainic systems. We used  
154 outcrops for the Los Zerpa site (Carrillo et al., 2006), and cores and outcrops for the Mucubají  
155 site (Carrillo et al., 2008). For both sedimentary fills, we performed different analyses and  
156 interpretative approaches aiming to detect and characterize specific layers and sedimentary  
157 features induced by seismic shaking, as proposed for alpine lakes (Chapron et al., 1999; Beck,  
158 2009). The here-discussed results are based on the data published in 2006 and 2008 (Carrillo  
159 et al., 2006, 2008) and on new data and interpretations:

- 160 1) additional field observations (Los Zerpa lacustrine and deltaic sediments and Mucubají  
161 Lake's watershed for surface structural features);
- 162 2) additional laboratory analysis on Lake Mucubají cores (sediments textures, Organic  
163 Matter characterization through Rock-Eval pyrolysis, new  $^{14}\text{C}$  measurements and  
164 calibrations, Table 1).

165 Within the frame of the same investigation program, two trenches had been achieved and  
166 analysed: respectively at Morro de Los Hoyos and Mesa del Caballo sites (Audemard et al.  
167 1999; 2008). For the following comparison we used their complete raw chronological results.

168

#### 169 **3.1. The Los Zerpa paleolake**

170 This well-preserved simple glacial system (Fig. 2-A and Fig. 4) displays numerous  
171 fractures affecting the lateral moraines, and the major Boconó Fault active trace which offsets  
172 the frontal morainic arc (see also Schubert, 1981). Microtectonic observations on the major  
173 trace (30° dipping slickensides on fine-grained lacustrine sediments) indicate a normal/right  
174 lateral movement. Successive abandoned outlets with slightly decreasing altitudes can be  
175 observed.

176 Imbricated terraces are related to episodes of emptying of the lake which have been  
177 attributed to major co-seismic displacement leading to rupturing of the frontal moraine  
178 (Carrillo et al., 2006). Between the lake genesis and its definitive emptying, the sedimentary  
179 infilling was interrupted at least three times. The rather simple depositional system, related to  
180 a unique tributary, can be divided into a lacustrine part with fine-grained laminated  
181 bottomsets, and a complex deltaic part. Carrillo et al. (2006) investigated the downstream part  
182 where they could recognize both specific deposits synchronous with local fracturing and post-  
183 depositional disturbances (slumping above liquefied layers). Our new works were dedicated  
184 to the upstream deltaic part in order to check a possible influence of the large landslide  
185 bounding the whole Quaternary deposits (Audemard et al., 2010) (Fig. 3-A). Deformation  
186 within the upstream part are mainly related to slumping; 3 major sliding surfaces were  
187 observed (outcrops close up in Carrillo et al, 2006, Fig.6 and 7). Beside highly variable dips  
188 of foreset layers, several discontinuities appear followed by coarse-grained “onlapping” layers  
189 with upstream fining. We interpret these layers as due to temporary powerful upslope currents  
190 with transport of coarse material (up to few cm gravels). At the top of the different foreset  
191 units, a centimetric to decimetric fine-grained laminated episode is draping the coarser  
192 sediments. The topmost millimetres, enriched in organic matter, provided 6 almost regularly  
193 spaced <sup>14</sup>C dates between 500 and 2000 yr cal. BP. A chronology of the different Los Zerpa  
194 deposits is discussed in Carrillo et al. (2006).

195 The upstream prolongation of the deltaic set is more complex and highly deformed,  
196 with extensional ruptures. The uppermost outcropping layers are downstream-dipping with  
197 different angles and fractured unconformities. We associate all the above-mentioned features  
198 to major co-seismic displacements of the Boconó Fault, along a portion which, at least,  
199 includes the segment crossing the Los Zerpa paleo-lake. A detailed model for one of these  
200 events, similar for Los Zerpa and Mucubají sites, is presented here-after (§ 3.3 and §3.4).

201

## 202 **3.2. Lake Mucubají**



203 About 5 km South-West of Los Zerpa paleolake, Lake Mucubají (or “Laguna de  
204 Mucubají”), is a 16 m-deep, still active, lacustrine basin at 3560 m a.s.l.. Short gravity cores  
205 and longer piston core (up to 8 m) were retrieved close to one of the two fault traces (Fig. 5).  
206 Isolated outcrops have been attributed to an initial much larger lake (Salgado-Labouriau et al.,  
207 1977; Carrillo et al, 2008). Although strongly depending on the seismo-tectonic setting, this  
208 sedimentary archive permitted to also detect the global climatic episodes (Carrillo et al.,  
209 2008). The southern part of the “paleo-lake Mucubají” was cut by a large deep-seated  
210 landslide separating the quaternary sediments from their rocky Precambrian basement  
211 (Audemard et al., 2010) (Fig. 3-B and white arrows on Fig. 5). The bottom of core MUCL-02-  
212 02 is dated back to the cal.  $^{14}\text{C}$  16 340/15 390 yr BP interval. For detailed description and  
213 analyses performed on cores and outcrops, we refer to Carrillo et al. (2008). In order to detect  
214 and characterize specific layers for paleoseismic investigation, different parameters were used  
215 for sediments composition and texture. Several abrupt changes in organic and mineral  
216 sources, and particular depositional processes, may argue for the co-seismic local origin of  
217 several major sedimentary “events”. As for the Los Zerpa paleolake, these events appear  
218 recorded through gravity reworking and reflected “tsunami” effects. We selected one of these  
219 events - considered as related to co-seismic rupturing of the Boconó Fault across the  
220 investigated lakes - to illustrate hereafter both Los Zerpa and Mucubají sedimentary archives.

### 222 3.3.. Sedimentological characterization of a single major event

223 Although the selected event (dated back to around 13 kyr BP) was detected and analysed  
224 in Core MUCL0202 from Mucubají site (Fig. 6), all evidenced sedimentary processes have  
225 also been observed in Los Zerpa site. The 41 cm-thick complex succession of layers is  
226 intercalated between two intervals of slow (“normal” or “background”) sedimentation.

227 The earthquake-related “event” (core close up on Fig. 6) consists in a succession of layers  
228 which we related to different phases of reworking and subsequent re-settling. Basically, it  
229 resembles a turbidite in a very broad sense, but several neat particularities have to be  
230 underlined:

- 231 1) a poorly sorted coarse base, lacking transition with overlying deposit,
  - 232 2) reworked mudclasts (indicating microfracturing of previously deposited coherent mud),
  - 233 3) indication of two opposite transport directions;
  - 234 4) sharp basal limit of the final homogeneous fine-grained settling.
- 235 Furthermore, the end of the fine-grained plume settling shows: i) a specific chemical and  
236 mineralogical concentration (vivianite), possible consequence of strong P release from bottom

237 sediments during shaking, ii) concentration of particulate O.M. which was used for  $^{14}\text{C}$  dating  
238 of the event. The association of the above-mentioned features corresponds to the  
239 “turbidite+homogenite” model as defined in lakes and marine semi-closed basins (Chapron et  
240 al., 1999; McHugh et al., 2006, 2011, 2014; Beck, 2009; Beck et al., 2007; Campos et al.,  
241 2013) and attributed to major earthquake-induced gravity reworking, *in situ* disturbances, and  
242 possible seiche effect.

243 In addition, sediments underlying and overlying this event are significantly different.  
244 Among different parameters (layering, grain size, mineralogy and chemistry) we selected the  
245 characteristics of Organic Matter content to illustrate a major and abrupt change synchronous  
246 with this event. ROCK-EVAL pyrolysis results (Fig. 6) indicated that O.M. content and  
247 characteristics also changed. With respect to underlying sediments, we noticed: increased  
248 COT, increased HI, decreased and stabilised OI. The whole evidences an abrupt increase of  
249 *in situ* lacustrine OM and more reducing conditions.

250

#### 251 **3.4. Interpretative model for major sedimentary events: impact of *in situ* co-seismic** 252 **rupturing.**

253 Figure 7 depicted two steps of the structural evolution of Lake Mucubají while Figure 8 is  
254 a tentative 2D model illustrating the successive sedimentary processes involved in one single  
255 major event in Los Zerpa paleo-lake. This mechanism is also entirely available for the  
256 sedimentary events observed in Lake Mucubají, especially the one presented and depicted in §  
257 3.3 (Fig. 6). For both sites, we assumed that, in addition to the Boconó Fault main strand,  
258 other rupturing occurred within, and at the base of, the morainic sediments pile. The 12 650-  
259 13 150 yr BP event (Fig. 7-A) is considered as responsible for a major morphological change  
260 (size and depth) and the coeval sedimentary event; a similar more recent event (Fig. 7-B) was  
261 also depicted (Carrillo et al., 2008).

262 On Figure 8, depicting the details of the sedimentation during one single major event in  
263 Los Zerpa site, step B corresponds to the tectonic *s.s.* triggering: the unconsolidated sediments  
264 (lacustrine deposits and bounding moraines) undergo fracturing with partial to total separation  
265 from underlying units. The vertical component of the offset is inferred to play a major role for  
266 the water mass mobilization. Step B and C depict the effect of “backwash” responsible for  
267 removing sediments upstream; it can be compared to a small “channelized” tsunami. With  
268 steps C to E, we explain the different features mentioned by Carrillo et al. (2006) in the distal  
269 (bottomsets) lacustrine deposits. Step F should represent the quiet final settling of re-  
270 suspended fraction of the reworked material, including lighter organic particles (cf. Fig. 6

271 close up). Each unit defined within the deltaic foreset is believed to correspond to such a  
272 scenario. The whole process may be applied to Lake Mucubají evolution, with slight  
273 differences only concerning the position of involved fracturing.

274

#### 275 **4. Discussion: comparison with Mesa del Caballo y Morro de Los Hoyos trenches data.**

276 The two lacustrine archives provided paleoseismic records at about 5 km distance from  
277 each other, along the same active fault trace. In order to compare these data with results  
278 yielded by the two neighbouring trenches (Fig. 2), we need to ensure their relationships with  
279 local co-seismic rupturing, i.e. with displacements along the Boconó Fault strands crossing  
280 the two lakes/paleolakes. For several major events - as the 12 650-13 150 yr BP one (Fig. 7-  
281 A) - this relationship may be assumed. Conversely, we cannot rule out the impacts: i) of  
282 remote strong earthquakes along farther strand of the Boconó Fault, ii) of other active faults  
283 within or bounding the Mérida Andes as the Valera fault. At least for the historical seismicity  
284 (Audemard, 1997; Audemard et al., 1999; Pousse-Beltran et al., 2018), none of the major  
285 events known elsewhere along the Boconó Fault (south-westward or north-eastward) appear  
286 within our results. Thus, we propose to consider the two lacustrine archives as representing  
287 local events records. If comparing with historical seismicity the here-involved portion of the  
288 Boconó Fault main strand most probably represents only a part of the total rupturing segments  
289 with respect to estimated magnitudes which rather require few tens of kilometres (Audemard,  
290 1997; Audemard et al., 1999; Pousse-Beltran et al., 2018).

291 The Morro de los Hoyos and the Mesa del Caballo trenches were respectively dug across  
292 the south-eastern and the north-western traces (Fig. 2) (Audemard et al., 1999, 2008). To  
293 attempt correlations between the different paleoseismic registers, a precise and reliable  
294 chronology is requested, a point discussed hereafter.

295

#### 296 **4.1. Chronological uncertainties**

297 With respect to the types of discussed archives and the differences between the two  
298 lacustrine fills, tentative correlations of separate events, between the four sites, may only rely  
299 on coincidences of radiocarbon dates. Thus, the actual significance of the obtained ages and  
300 their precision have to be discussed. For all samples, a correction was applied to conventional  
301 AMS  $^{14}\text{C}$  ages using OxCal v4.3 software (Bronk Ramsey and Lee, 2013) considering only  
302 the atmospheric  $\text{CO}_2$  variations (IntCal123 curve, Reimer et al, 2013). The analysis of  
303 Organic Matter (O.M.), using Rock-Eval parameters (Espitalié et al., 1985) for Lake  
304 Mucubají cores (Fig. 6), indicates dominant terrestrial O.M. and minor lacustrine production.

305 Thus, and regarding the reduced sizes and depths of the lake basins, no reservoir effect  
306 correction was applied to the lacustrine samples.

307 For trenches data, the dated O.M. matter comes from soils or sag ponds vegetal  
308 accumulation. These measurements probably give a mean age for mixed organic debris which  
309 represent a time interval difficult to estimate. Most of the ages obtained from the two lakes  
310 represent fine-grained particulate O.M. settling at the end of reworking events (Carrillo et al,  
311 2008). In this case, dated samples have a more precise position with respect to the earthquake-  
312 induced layer, but the reworked thickness from previous deposits may also induce a mixing of  
313 not contemporaneous O.M. particles. Table 1 concerns AMS  $^{14}\text{C}$  data previously published  
314 and new results; for the trenches, we used already published results (Audemard et al, 1999,  
315 2008) and the same re-calibration was applied to all values. Tentative correlations between  
316 the events from the four sites (Fig. 9) are based on the complete  $^{14}\text{C}$  error bars ( $2\sigma$ , 95.4 %  
317 prob.). The last 10 000 years BP (almost the entire Holocene) could be checked.

318

#### 319 **4.2. Tentative correlations between the two trenches and the two lacustrine records**

320 For the following discussion, we first assume that all fracturing episodes detected and  
321 dated in trenches have to be taken into account (Fig. 9-A and Fig. 10). Among a total of 24  
322 inferred seismic events (Fig. 9-B), only 3 may be *correlated for three sites*, including one or  
323 two lake fills and one or two trenches. 3 other *correlations between two sites - one lake fill*  
324 *and one trench* - may be added. An overall mean 400 yr return interval may be deduced;  
325 published historical “frequency” is higher but it concerns to a much longer portion of the  
326 Boconó Fault (§ 2.1; Audemard, 1997). If comparing with the north-east portion of the  
327 Boconó Fault recently surveyed (Pousse-Beltran et al., 2018) no historical mutual event  
328 appears.

329 For *Lake Mucubají*, only few events were detected, but they all have a possible equivalent  
330 in other sites. This may indicate that, during part of the last 10 kyr BP, sedimentation was not  
331 favourable for shock-induced reworking (e.g. slow rate with cohesive deposits) and that only  
332 *the strongest and local events* were registered. The about 9 kyr BP event (Fig. 7-A) illustrates  
333 this case. The results for the *Los Zerpa paleo-lake* appears partly different as the “quiet”  
334 interval between 2 kyr and 7.5 kyr BP is due to a gap in sedimentary infilling (see § 3.1).

335 According to *trench data*, many possible correlations appear between the two traces prior  
336 to 2.5 kyr BP. No more events are detected on north-western trace, whilst several are detected  
337 on the south-eastern trace; furthermore, they have possible equivalents in Los Zerpa lacustrine  
338 archive. As noticed on Figure 9-A, ending of the north-western trace may be proposed, with a

339 continuation on the south-eastern trace. An alternate hypothesis is to consider the north-  
340 western trace as a more temporary, or a secondary, one (Audemard et al., 2010). Our initial  
341 assessment - to consider all rupturing phases dated in trenches as major earthquake marks -  
342 appears questionable.

343 However, the observed deformations only concern few hundreds of meters of  
344 unconsolidated sediments. These surficial structures may not exactly reflect the geometry of  
345 the Boconó Fault activity within the underlying basement, and the huge landslide (white line  
346 on Fig. 10; *cf.* also Audemard et al. (2010)) possibly plays a major role in co-seismic  
347 fracturing distribution. Future investigation (through trenching ?) should investigate this  
348 major structure.

349

### 350 **Conclusions**

351 Although we considered the studied area as particularly adequate to test the  
352 complementarity of lacustrine sedimentary archives and trench dating, possible correlations  
353 between very close sites could be *established only for part of the detected events*. The  
354 lacustrine records may partly confirm the results of trenching across the same active traces. At  
355 the difference, *large gaps* in studied lacustrine archives appear, at least partly filled by trench  
356 data. As the four sites are concentrated within a small area, it is unlikely to put forward the  
357 *distance* between the sedimentary accumulations and the *epicentral areas* as a limiting factor  
358 for lacustrine recording. Furthermore, for major events (approx. 9 kyr and 13 kyr BP, Fig. 7-A  
359 and 7-B), combined structural and sedimentological observations (§ 3.3 and 3.4) clearly  
360 evidence the association of “*intra-lake*” *co-seismic rupturing and sedimentary reworking*. In  
361 the here-studied case, a weak intrinsic potential for earthquake recording better explains the  
362 sedimentary “events” scarcity. In particular, shock-induced reworking may lack during  
363 periods of clayey cohesive slow sedimentation; for a deltaic foreset accumulation, a major  
364 reworking may sweep off a major amount of unconsolidated sediment and prevent new  
365 reworking during a time interval (in Beck, 2009).

366 More generally, these results also show that a unique sedimentary archive or a unique  
367 trench, *even for a well-known fault and within a small area*, may be an *incomplete or biased*  
368 record of local seismicity, and deduced seismic hazard assessment. The present attempt to  
369 combine lacustrine sedimentary archives and trench data points out two “opposite” biases:  
370 “incomplete” recording by sedimentation, and possible “overestimation” of co-seismic  
371 rupturing events deduced from trench analysis.

372

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586  
 587 **Figures captions:**

588  
 589 Figure 1.- Geodynamic and morphological settings of the Boconó Fault. A: *Morphology of*  
 590 *the*  
 591 *Merida Andes and location of the studied area. Shade relief from Garrity et al. (2004).*  
 592 *Epicentral location of several major historical earthquakes in central Merida*  
 593 *Andes, from Palme et al. (2005) and Audemard (2005). Insert B: South-Caribbean*  
 594 *geodynamics simplified from Audemard et al. (2000), Weber et al. (2001), Pérez et al.*  
 595 *(2001), Symithe et al. (2015).*

596 Figure 2.- Detailed morphology of the surveyed area, and location of the investigated sites. A  
 597 *set of morainic systems are crosscut and deformed by an active trace of the right*  
 598 *lateral strike slip Boconó Fault; several associated moraine-dammed lakes are also*  
 599 *affected by the fault activity. For the Los Zerpa site, the sedimentary fill is preserved*  
 600 *as outcrops; for the Mucubají site, part of the fill is still in sub-lacustrine position.*  
 601 *Aerial photos from Instituto Geográfico “Simón Bolívar” de Venezuela. (North*  
 602 *direction towards the left-bottom corner of the picture for better relief visibility). (AA’*  
 603 *and BB’: cross section displayed on Figure 3).*

604 Figure 3.- Geometry and Structural setting of Los Zerpa and Mucubají Late Quaternary  
 605 morainic and lacustrine deposits. (*Location of sections AA’ and BB’ on Figure 2*). 1)  
 606 *Precambrian metamorphic and igneous basement (gneisses, amphibolites, granites);*  
 607 *2) LGM morainic deposits; 3) post-LGM lacustrine deposits (for the Los Zerpa site,*

608 *they are represented at their altitude as viewed through lateral moraines). NB: scales*  
 609 *are different for the two sections.*

610 Figure 4.- Location of the different types of disturbances in the Los Zerpa paleo-lake fill  
 611 remnants. *Lacustrine sediments trapped within the Los Zerpa morainic system appear*  
 612 *as terraces. Earthquake-impacts are either direct fracturing (Gilbert-delta and bottom*  
 613 *sets) or gravity reworking and liquefaction (delta foresets and bottomsets). Aerial*  
 614 *photos from Instituto Geográfico “Simón Bolívar” de Venezuela. (North direction*  
 615 *towards the left-bottom corner of the picture for better relief visibility).*

616 Figure 5.- The Mucubají Lake and paleo-lake: morphological setting and location of coring  
 617 sites. (isobaths curves interval: 2 m). *Light grey area: outcropping lacustrine*  
 618 *sediments. White arrows underline the limit of a deep-seated landslide following*  
 619 *Audemard et al. (2013). Aerial photos from Instituto Geográfico “Simón Bolívar” de*  
 620 *Venezuela. (North direction towards the left-bottom corner of the picture for better*  
 621 *relief visibility)*

622 Figure 6.- Example of major sedimentary event in Lake Mucubají. *Layering, texture,*  
 623 *and composition (left), and deduced sedimentary processes (right), depict the*  
 624 *combined effect of gravity reworking and water mass oscillation. This complex event*  
 625 *corresponds to a “homogenite+turbidite” association. The chosen event exactly*  
 626 *precedes a major change of the lake size and sedimentation (see Fig. 8-A) and is thus*  
 627 *considered as co-seismic with respect to an offset of the main strand of the Boconó*  
 628 *fault across the lake.*

629 Figure7.- Reconstruction of two inferred co-seismic modifications of Lake Mucubají in  
 630 relation with the Boconó Fault. *The scenario represented in A corresponds to the main*  
 631 *event displayed on Figure 6.*

632 Figure 8.- Reconstruction of a co-seismic sedimentary event related to an offset of the Boconó  
 633 Fault across the Los Zerpa paleolake. *This scenario is based on the sedimentary*  
 634 *structures and the specific layering observed in the different parts of the lacustrine fill*  
 635 *(detailed in Carrillo et al. 2006).*

636 Figure 9.- Synthesis of paleoseismic data from the Los Zerpa/Mucubají area, combining  
 637 trench data and lacustrine sedimentary archives. A) Tentative time correlations. *They*  
 638 *are based on overlapping of error bars corresponding to 2 $\sigma$  intervals of Calibrated*  
 639 *<sup>14</sup>C ages. Correlations concern the 10 last kyr BP. Trench data provide a more*  
 640 *regularly distributed set of data, while lacustrine archives give two periods with*  
 641 *recorded events (2 kyr to Present, 10 to 8 kyr BP); several possible correlations*

642 *between trenches and lacustrine fills may be proposed for these two periods.*  
643 *Combined data indicate a possible dis-activation of the North-West trace with a*  
644 *coeval continuation of the South-East trace. Insert B) Summary of trenches and*  
645 *lacustrine data for the last 10 kyr BP.*

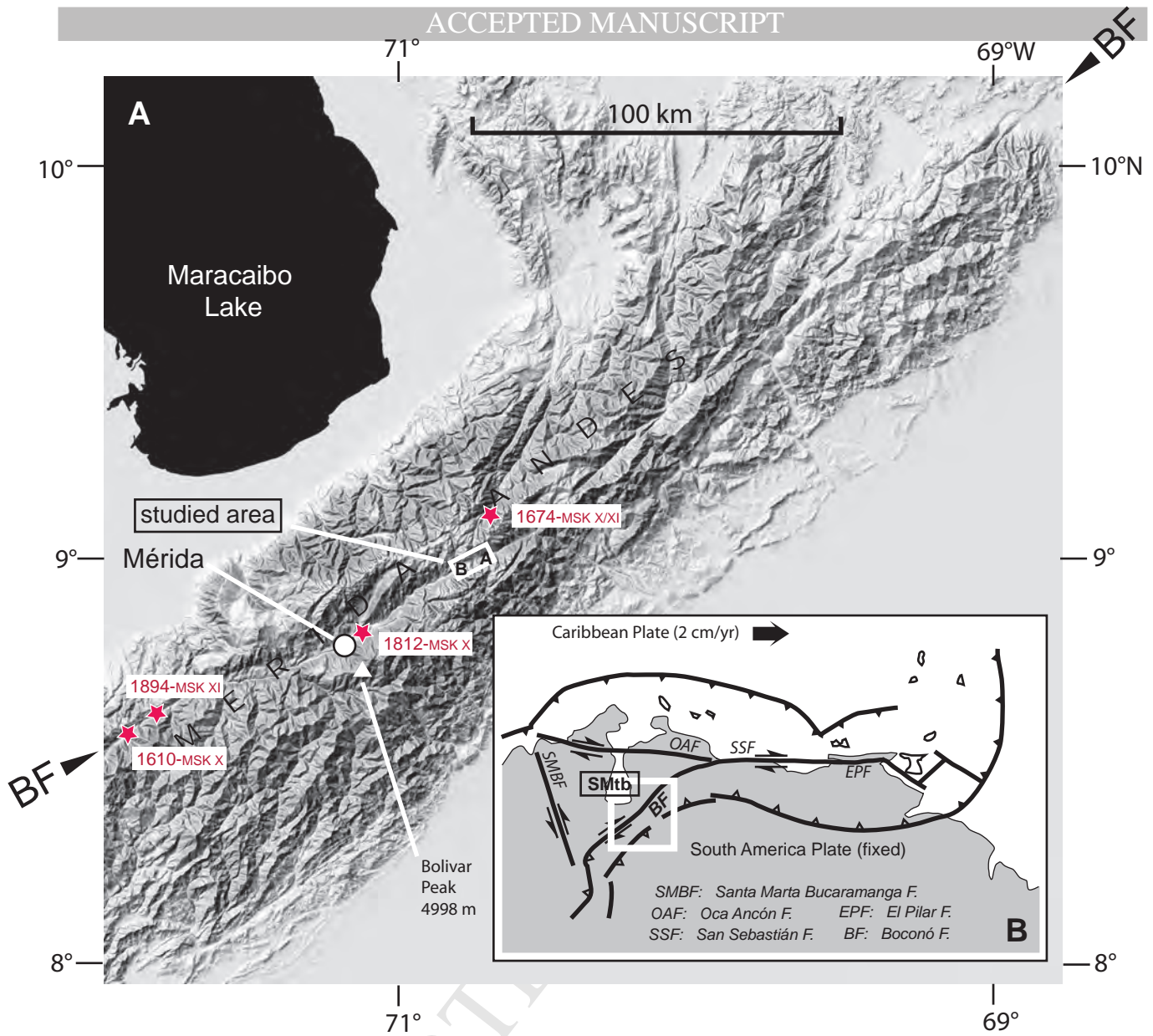
646 Figure 10.- Geographical distribution and summary of paleoseismic data sources in the Los  
647 Zerpa/Mucubají Area.

648 Table 1:  $^{14}\text{C}$  dating results for the lacustrine sedimentary archives. *Compilation of Carrillo et*  
649 *al. (2006, 2008)'s data and additional unpublished measurements. LZAF: Los Zerpa*  
650 *paleo-lake; MUCL: Lake Mucubají cores samples.*

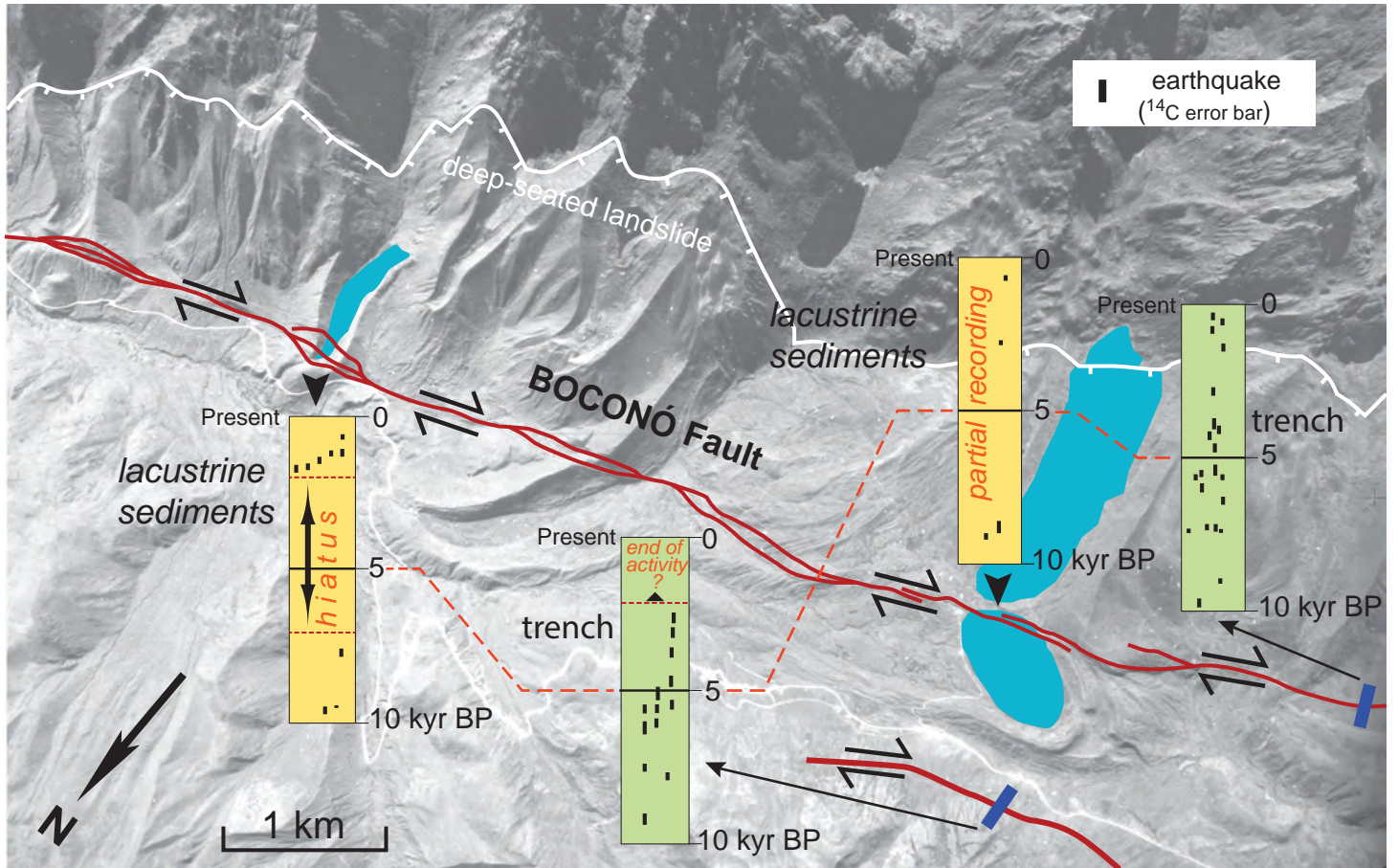
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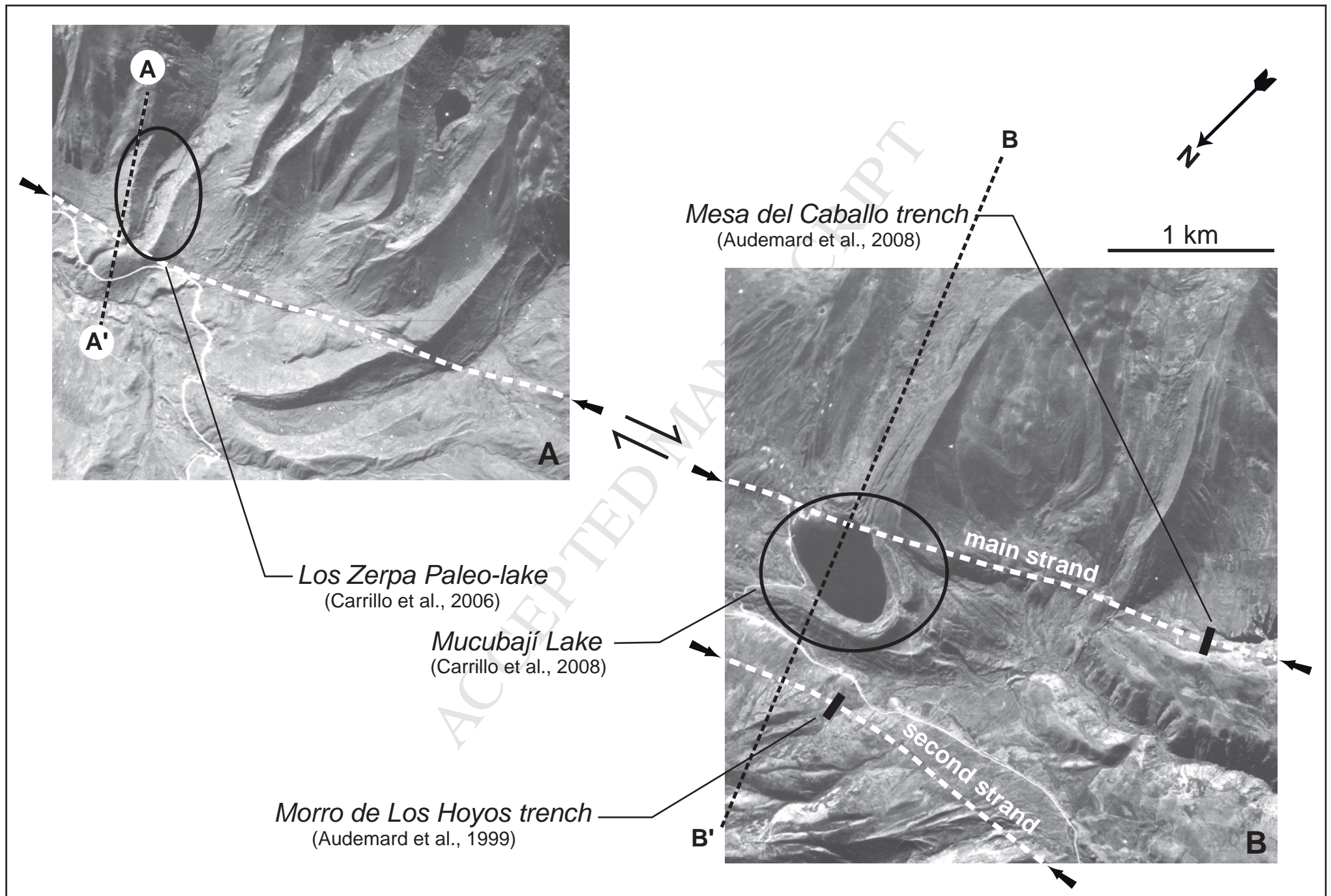
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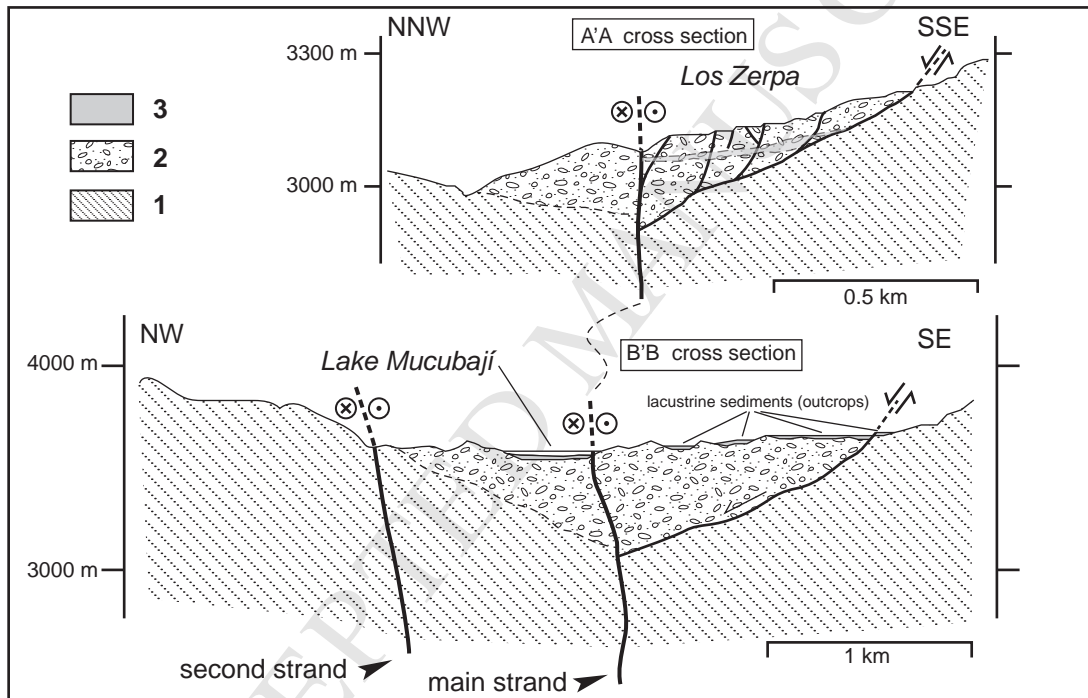
<b>Sample</b>	<b>Conventional <sup>14</sup>C age yrs BP</b>	<b>Calibrated BP age ; 95.4 % probability yrs BP</b>
MUCL-02-01-60	8180 ± 60	9000/9400
MUCL0201-02A30	9620 ± 50	10750/11170
MUCL-02-01-176	10490 ± 50	12050/12900
MUCL-02-01-203	10910 ± 60	12650/13150
MUCL-02-01-269	11750 ± 70	13350/14150
MUCL-02-0- 453	13200 ± 80	14850/16450
MUCL-02-02-150	2630 ± 50	2700/2860
MUCL-02-023A90	7890 ± 50	8580/8990
MUCL-02-02-590	10800 ± 90	12600/13150
MUCL-02-02-800	13200 ± 120	14850/16450
LDMU-04-3	750 ± 40	640/740
LZAF-04 1	760 ± 40	650/760
LZAF-04 2	1280 ± 40	1080/1290
LZAF-04 3	1550 ± 50	1330/1540
LZAF-04 4	1290 ± 40	1120/1300
LZAF-04 5	1800 ± 40	1600/1830
LZA-6 C1	1755 ± 40	1550/1740
LZA-4-4MO1	8500 ± 50	9430/9550
LZA-4-4MO2	8590 ± 50	9480/9700
LZA-AL-SU-1	6870 ± 60	7580/7830

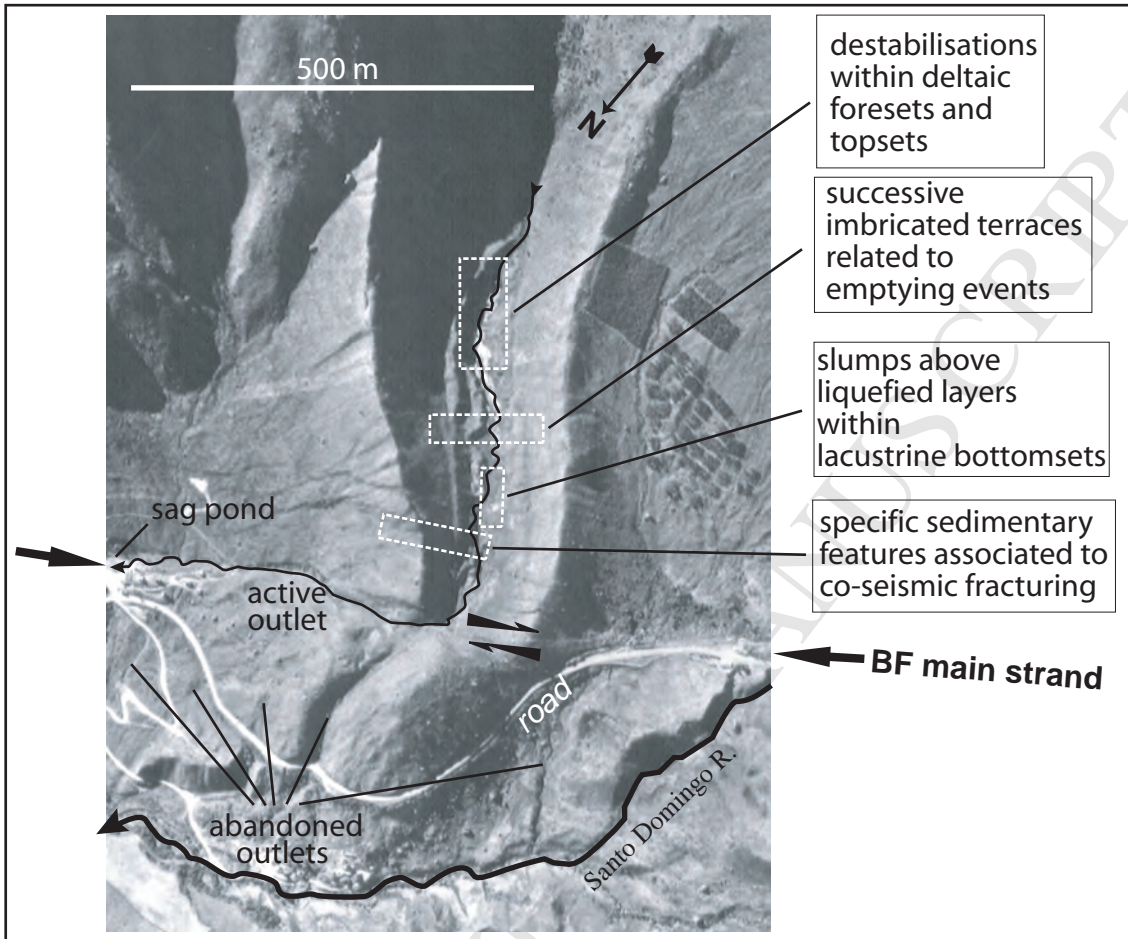




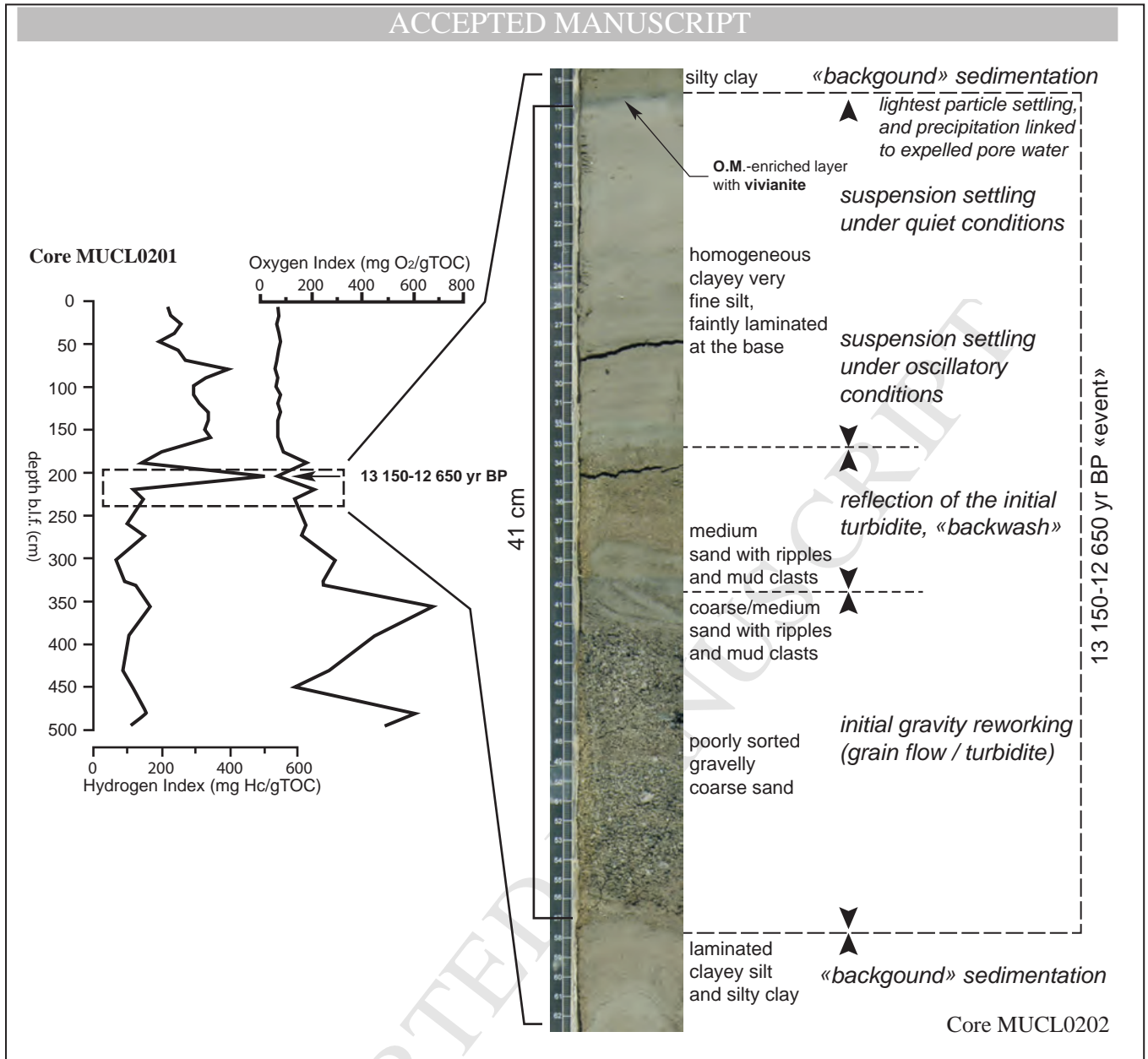


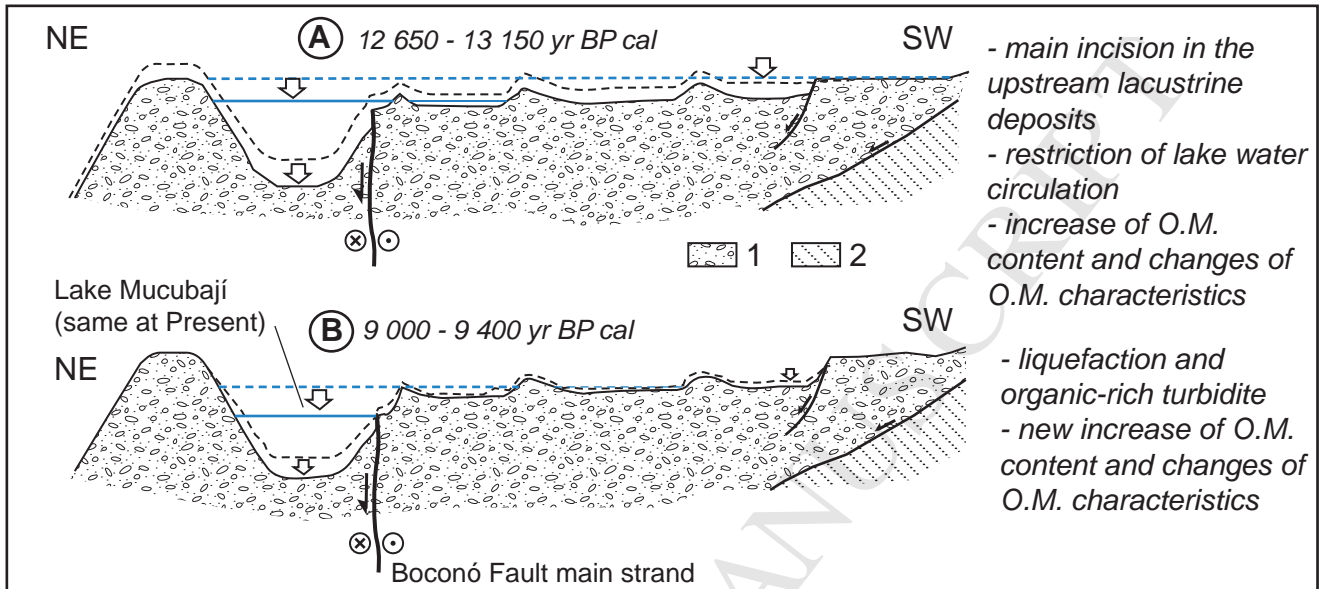


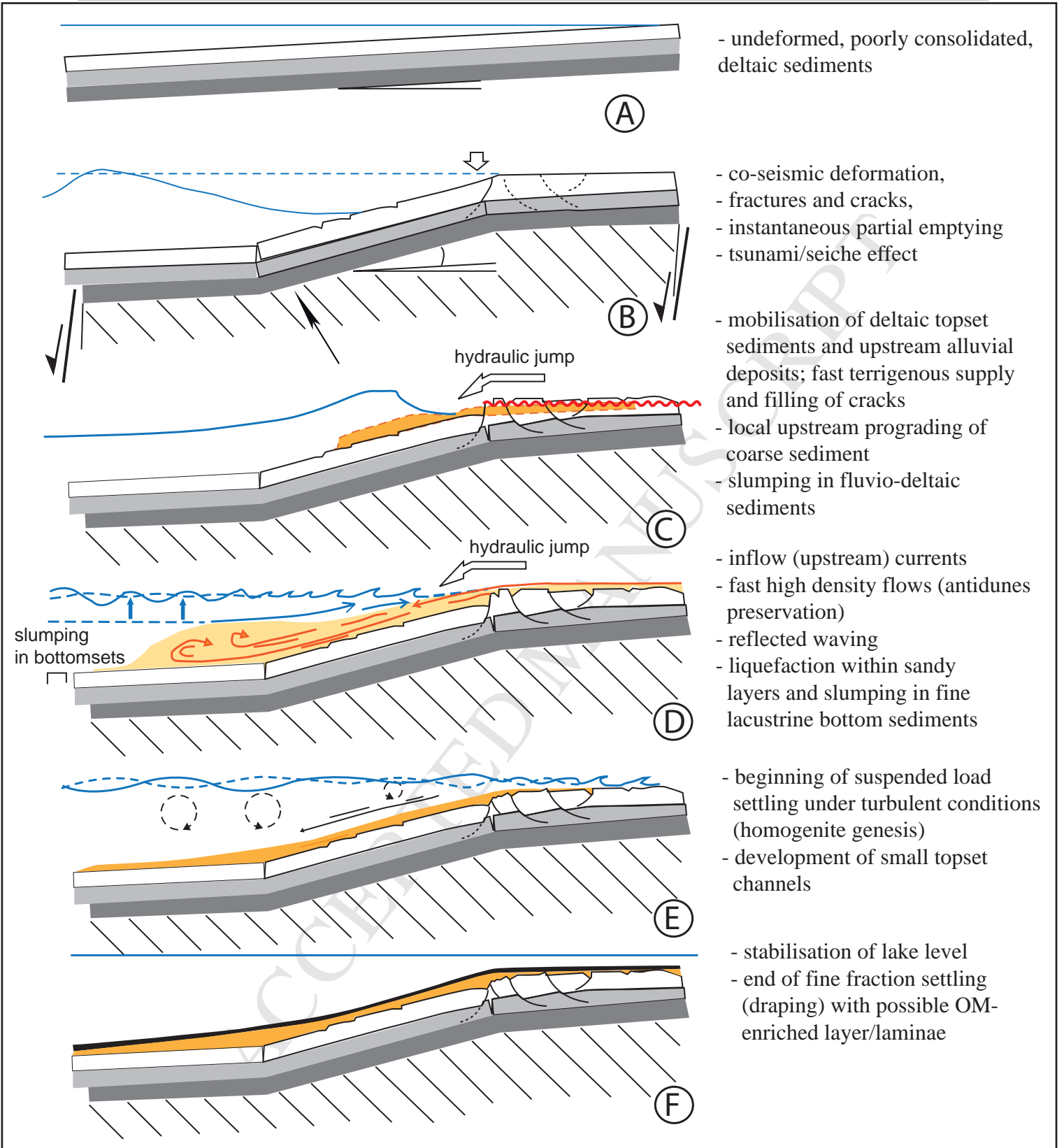




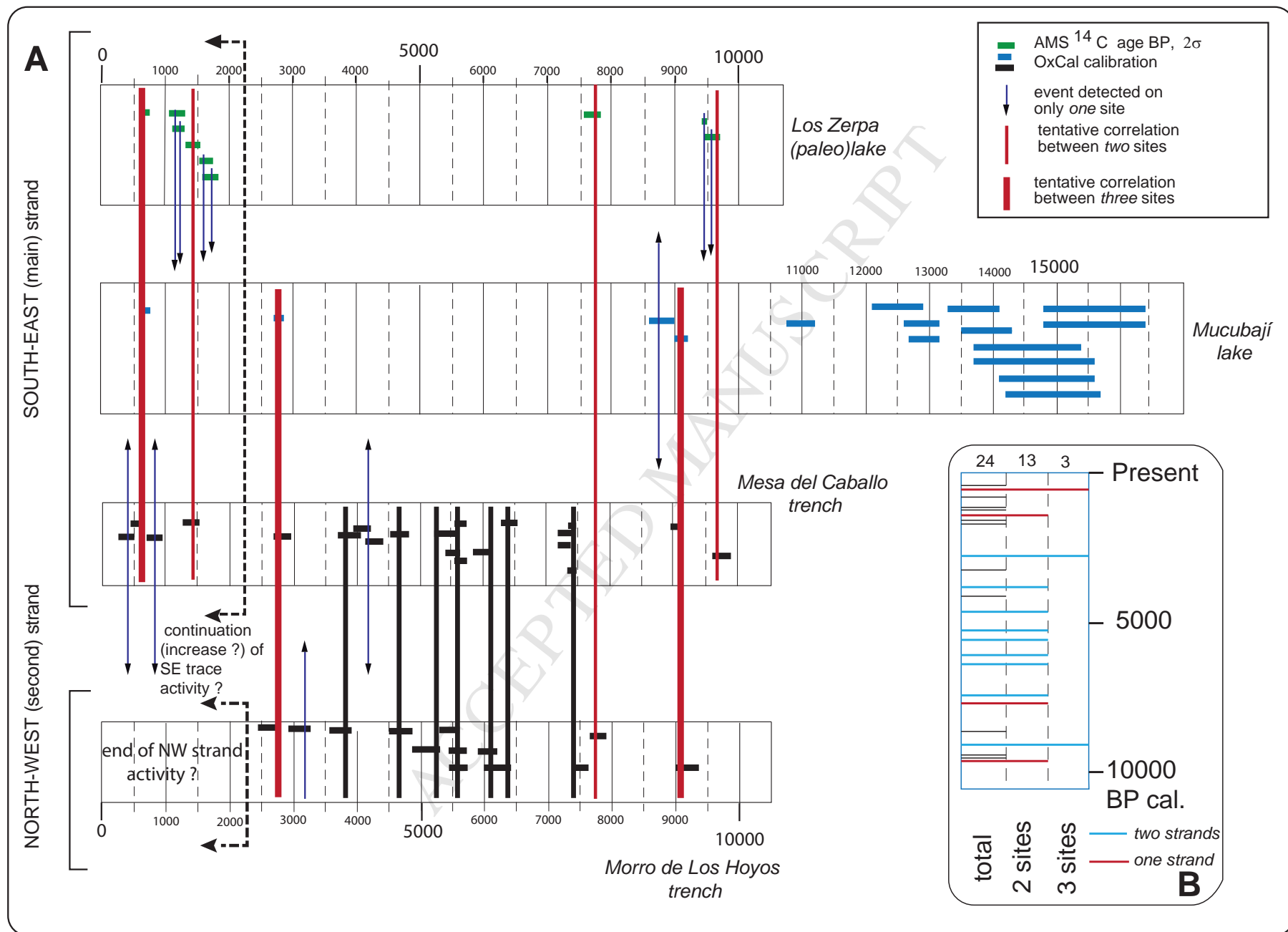












Along an active seismogenic strike slip fault - the Boconó Fault, Mérida Andes, Northwestern Venezuela - a 7 km long strand offers a unique situation to combine, for paleoseismic purpose, two lacustrine sedimentary records and two trenches. For a 10 kyr record, tentative correlations are presented: among a total of 24 inferred seismic events, only 3 may be correlated for three sites, including one or two lake fills and one or two trenches. 3 other correlations between two sites - one lake fill and one trench - may be added. An overall mean 400 yr return interval may be deduced, which appears longer than historical events return period. These results show that a unique sedimentary archive or a unique trench, even for a well-known fault and within a small area, may be an incomplete or biased record of local seismicity, and deduced seismic hazard assessment. The present attempt to combine lacustrine sedimentary archives and trench data points out two “opposite” biases: “incomplete” recording by sedimentation, and possible “overestimation” of co-seismic rupturing events deduced from trench analysis.