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**Abstract**

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

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

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

## 1. Introduction:

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

To our knowledge, the combination of trench data and lacustrine sedimentary archives, both related to the same active seismogenic fault, has scarcely been attempted. The here-presented work concerns a favourable site for such combined approaches: the central part of the Mérida Andes (North-western Venezuela) crosscut by the Boconó Fault. Within the frame of the same research program, we could achieve: outcrop analyses, lake sediments coring, and trenching. The present article presents the last phase of these investigations: an attempt to integrate trenches results published in 1999 and 2008, and lacustrine archives data published in 2006 and 2008. The here-discussed data combined these results with new additional investigations dedicated: 1) to lacustrine sediments depositional processes and chronology, 2) to deep-seated gravitational slope deformations bounding the Boconó Fault (Audemard et al., 2010), 3) to the chronology of the last deglaciation using cosmogenic isotopes (Carcaillet et al., 2013). Thus, for the following, we present as new data: a final interpretation of sedimentological investigations, including structural positions, and a completed chronology of all compared events.

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

### 2.1. Geodynamic and tectonic setting

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

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

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

**2.2. Imprint of the last climatic cycles in central Merida Andes**

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

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

Beside their high paleoclimatic interest, the Mérida Andes' glacigenic and post-glacial sedimentary bodies were soon used as precious tectonic benchmarks to quantify the Boconó Fault activity (Schubert, 1982). Most of them are crosscut by surface-reaching active traces, and horizontally displaced (Fig. 2). We focused our work on two of these morainic systems and their associated lacustrine sedimentary fills: the Los Zerpa site and the Mucubají site. A major south-eastern active trace and a less visible north-western trace were chosen for structural and paleoseismic analyses in trenches (Audemard et al., 1999, 2008). The south-eastern active trace just bounds the Los Zerpa lacustrine sediments (Fig. 3, section AA') while it crosscuts Lake Mucubají (locally named "Laguna de Mucubají") (Fig. 3, section BB'). A minor transtensional component also characterizes the studied portion of the Boconó Fault, indicated by: normal ruptures within moraines, "micro pullapart" depressions or sagponds, and low angle NE-dipping slickendides. In the Los Zerpa/Mucubají área, a large north-westwards landslide displaces the whole Late Quaternary pile on the southeastern side of the fault (Audemard et al., 2010). This gravitational deformation is also related to the local transtensional component and inferred to be activated by strongest earthquakes (Audemard et al., 2010; and this work).

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

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

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

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

### 3.1. The Los Zerpa paleolake

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

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

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

### 3.2. Lake Mucubají

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

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

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

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

1) a poorly sorted coarse base, lacking transition with overlying deposit,
2) reworked mudclasts (indicating microfracturing of previously deposited coherent mud),
3) indication of two opposite transport directions;
4) sharp basal limit of the final homogeneous fine-grained settling.

Furthermore, the end of the fine-grained plume settling shows: i) a specific chemical and mineralogical concentration (vivianite), possible consequence of strong P release from bottom sediments during shaking, ii) concentration of particulate O.M. which was used for $^{14}C$ dating of the event. The association of the above-mentioned features corresponds to the “turbidite+homogenite” model as defined in lakes and marine semi-closed basins (Chapron et al., 1999; McHugh et al., 2006, 2011, 2014; Beck, 2009; Beck et al., 2007; Campos et al., 2013) and attributed to major earthquake-induced gravity reworking, *in situ* disturbances, and possible seiche effect.

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

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

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

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

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

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

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

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

### 4.1. Chronological uncertainties

With respect to the types of discussed archives and the differences between the two lacustrine fills, tentative correlations of separate events, between the four sites, may only rely on coincidences of radiocarbon dates. Thus, the actual significance of the obtained ages and their precision have to be discussed. For all samples, a correction was applied to conventional AMS $^{14}C$ ages using OxCal v4.3 software (Bronk Ramsey and Lee, 2013) considering only the atmospheric $CO_2$ variations (IntCal123 curve, Reimer et al, 2013). The analysis of Organic Matter (O.M.), using Rock-Eval parameters (Espitalié et al., 1985) for Lake Mucubají cores (Fig. 6), indicates dominant terrestrial O.M. and minor lacustrine production.

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

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

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

For the following discussion, we first assume that all fracturing episodes detected and dated in trenches have to be taken into account (Fig. 9-A and Fig. 10). Among a total of 24 inferred seismic events (Fig. 9-B), 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; published historical “frequency” is higher but it concerns to a much longer portion of the Boconó Fault (§ 2.1; Audemard, 1997). If comparing with the north-east portion of the Boconó Fault recently surveyed (Pousse-Beltran et al., 2018) no historical mutual event appears.

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

According to *trench data*, many possible correlations appear between the two traces prior to 2.5 kyr BP. No more events are detected on north-western trace, whilst several are detected on the south-eastern trace; furthermore, they have possible equivalents in Los Zerpa lacustrine archive. As noticed on Figure 9-A, ending of the north-western trace may be proposed, with a continuation on the south-eastern trace. An alternate hypothesis is to consider the north-western trace as a more temporary, or a secondary, one (Audemard et al., 2010). Our initial assessment - to consider all rupturing phases dated in trenches as major earthquake marks - appears questionable.

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

**Conclusions**

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

More generally, these results also 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.

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**Figures captions**:

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

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

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

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

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

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

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

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

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

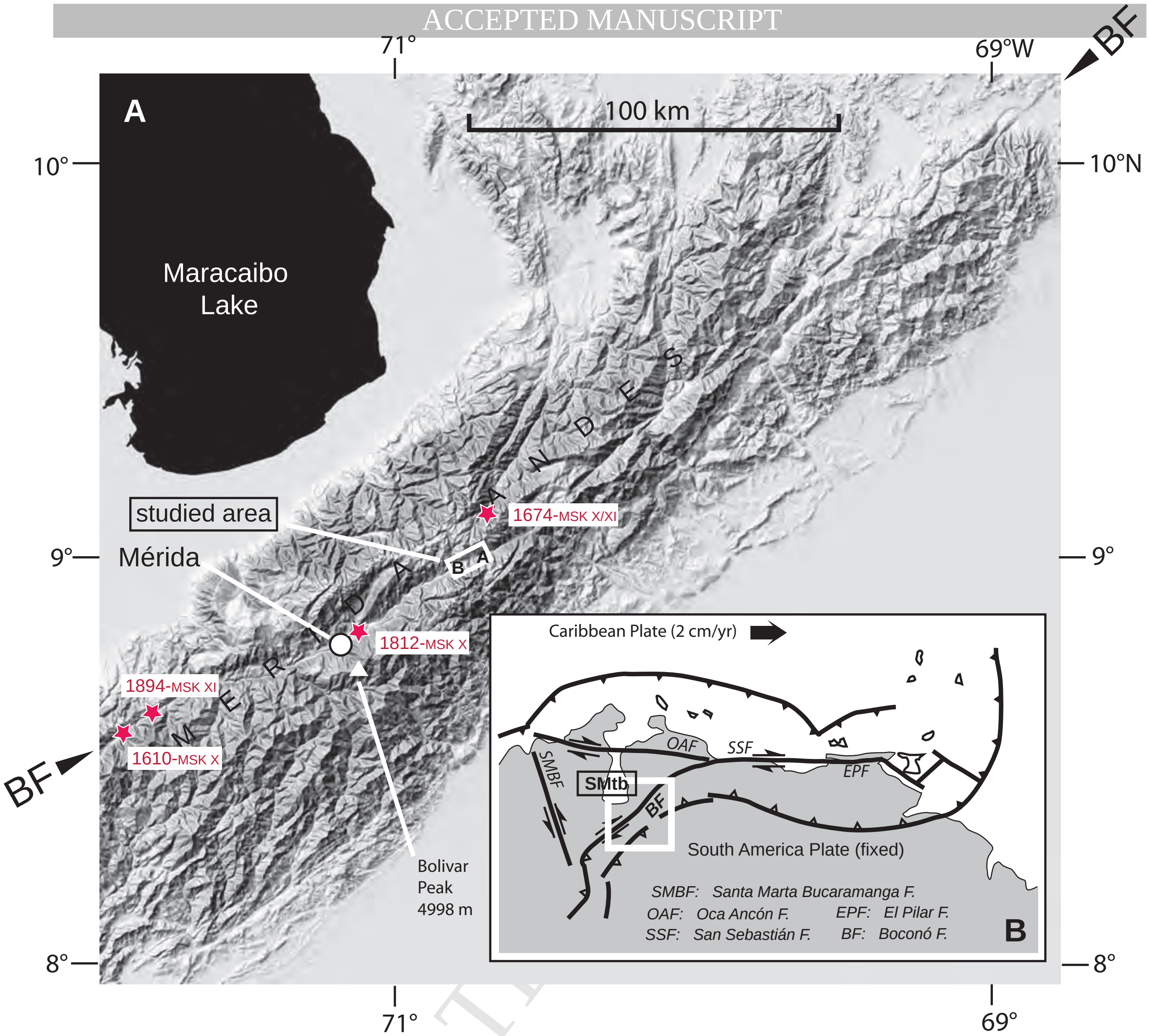
Figure 9.- Synthesis of paleoseismic data from the Los Zerpa/Mucubají area, combining trench data and lacustrine sedimentary archives. A) Tentative time correlations. *They are based on overlapping of error bars corresponding to $2\sigma$ intervals of Calibrated $^{14}C$ ages. Correlations concern the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

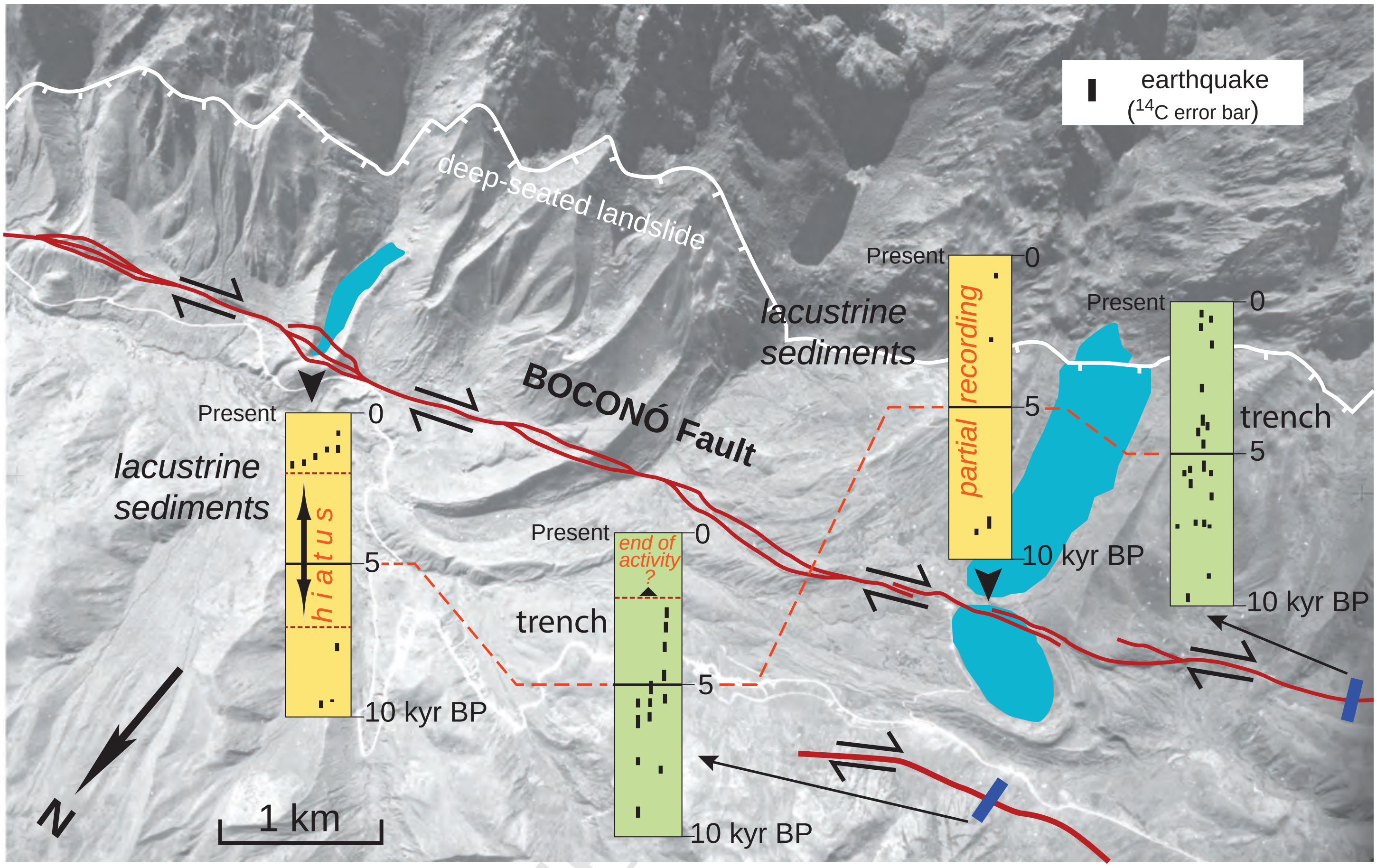
*between trenches and lacustrine fills may be proposed for these two periods. Combined data indicate a possible dis-activation of the North-West trace with a coeval continuation of the South-East trace*. Insert B) Summary of trenches and lacustrine data for the last 10 kyr BP.

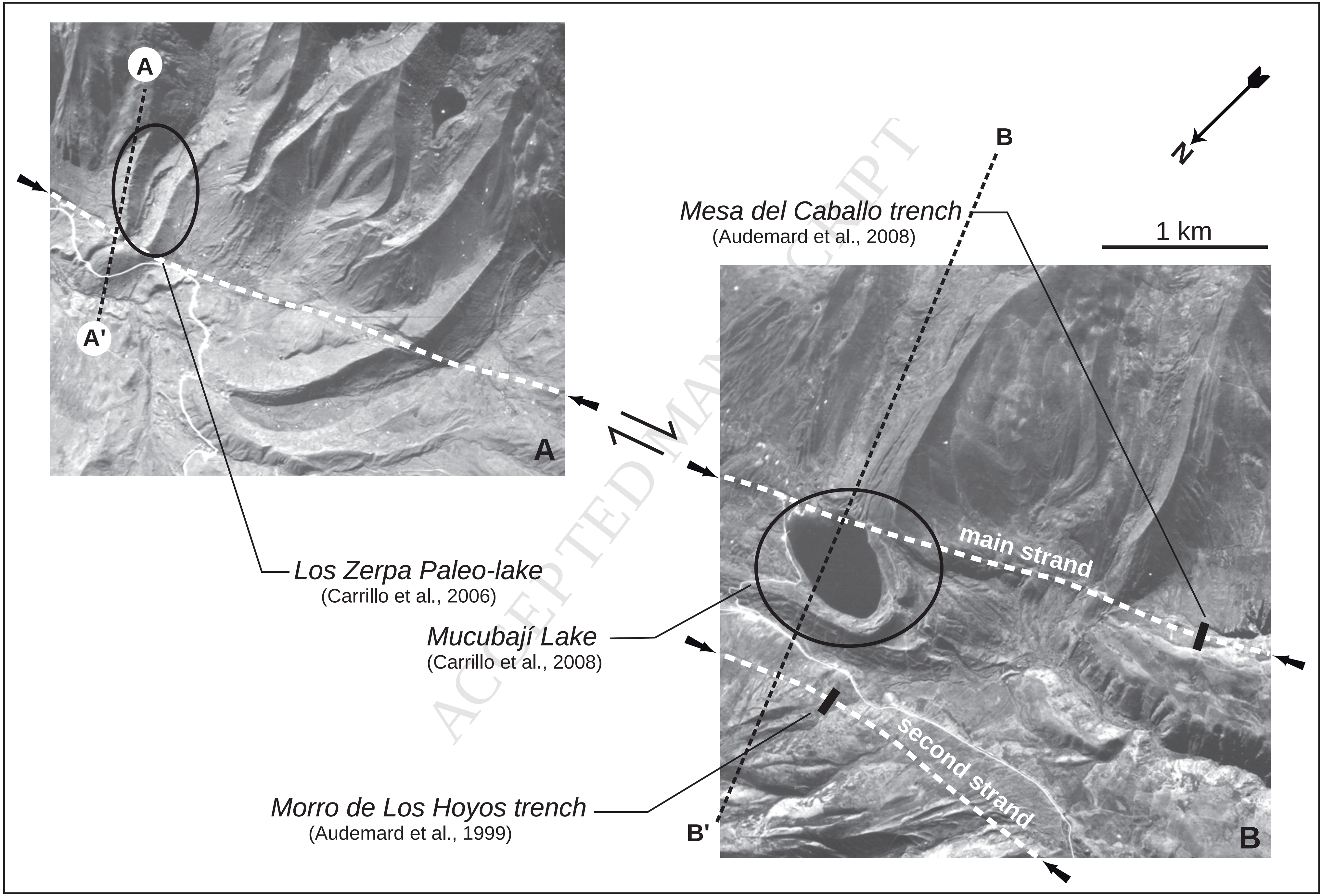
Figure 10.- Geographical distribution and summary of paleoseismic data sources in the Los Zerpa/Mucubají Area.

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

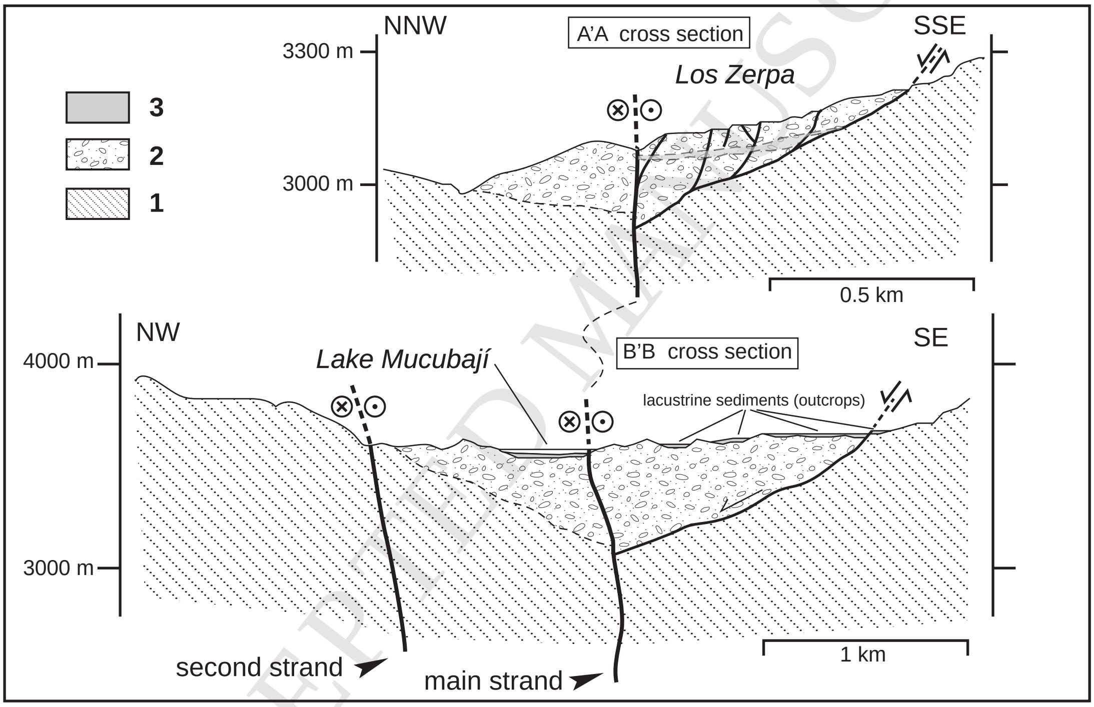
| Sample | Conventional $^{14}C$ age yrs BP | Calibrated BP age ; 95.4 % probability yrs BP |
|---|---|---|
| MUCL-02-01-60 | 8180 ± 60 | 9000/9400 |
| MUCL0201-02A30 | 9620 ± 50 | 10750/11170 |
| MUCL-02-01-176 | 10490 ± 50 | 12050/12900 |
| MUCL-02-01-203 | 10910 ± 60 | 12650/13150 |
| MUCL-02-01-269 | 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 |


71°
69°W
BF
A
100 km
10°
10°N
Maracaibo
Lake
M E R I D A   A N D E S
studied area
Mérida
9°
9°
1674-MSK X/XI
1812-MSK X
1894-MSK XI
1610-MSK X
BF
Bolivar
Peak
4998 m
Caribbean Plate (2 cm/yr)
OAF
SSF
EPF
SMBF
SMtb
BF
South America Plate (fixed)
SMBF: Santa Marta Bucaramanga F.
OAF: Oca Ancón F.
SSF: San Sebastián F.
EPF: El Pilar F.
BF: Boconó F.
B
8°
8°
71°
69°

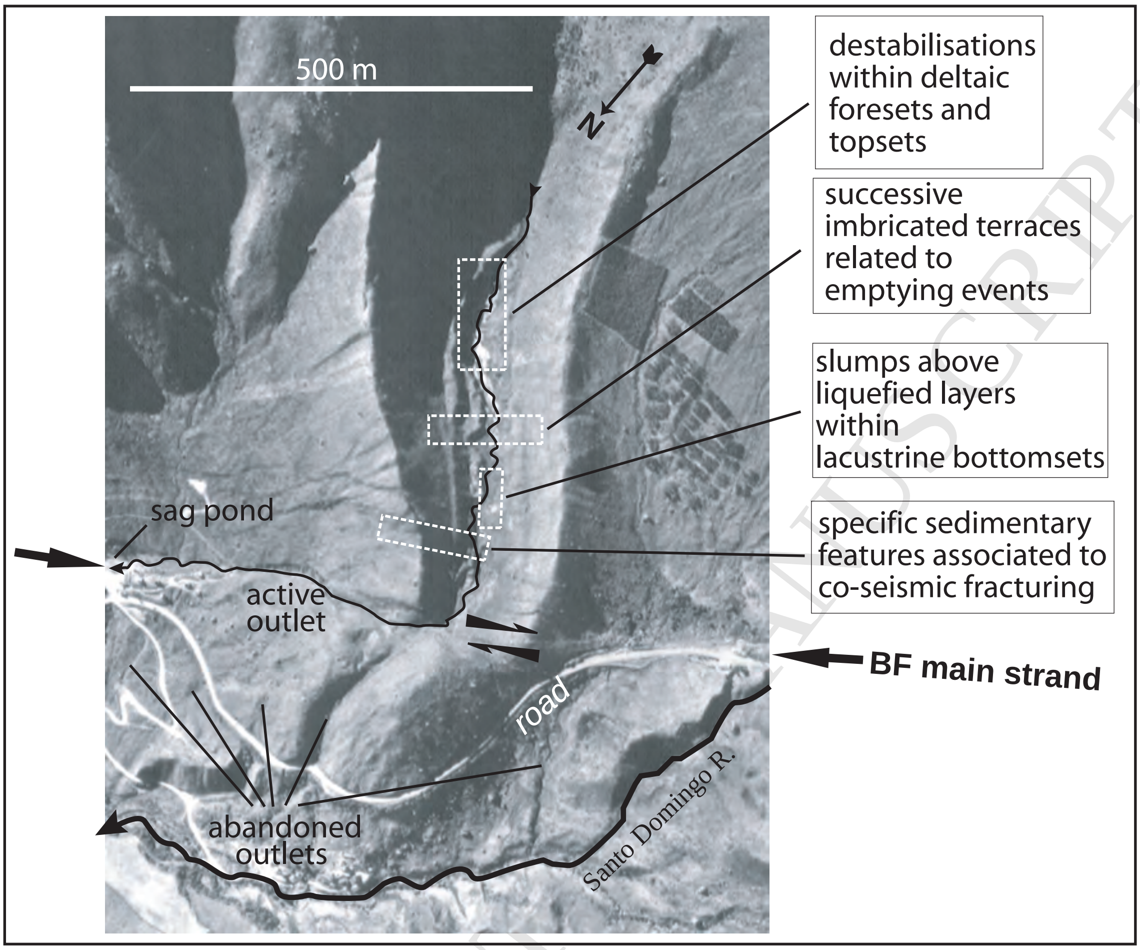

earthquake
(14C error bar)
deep-seated landslide
lacustrine
sediments
BOCONÓ Fault
Present
0
5
10 kyr BP
partial recording
hiatus
trench
end of activity
?
1 km
N

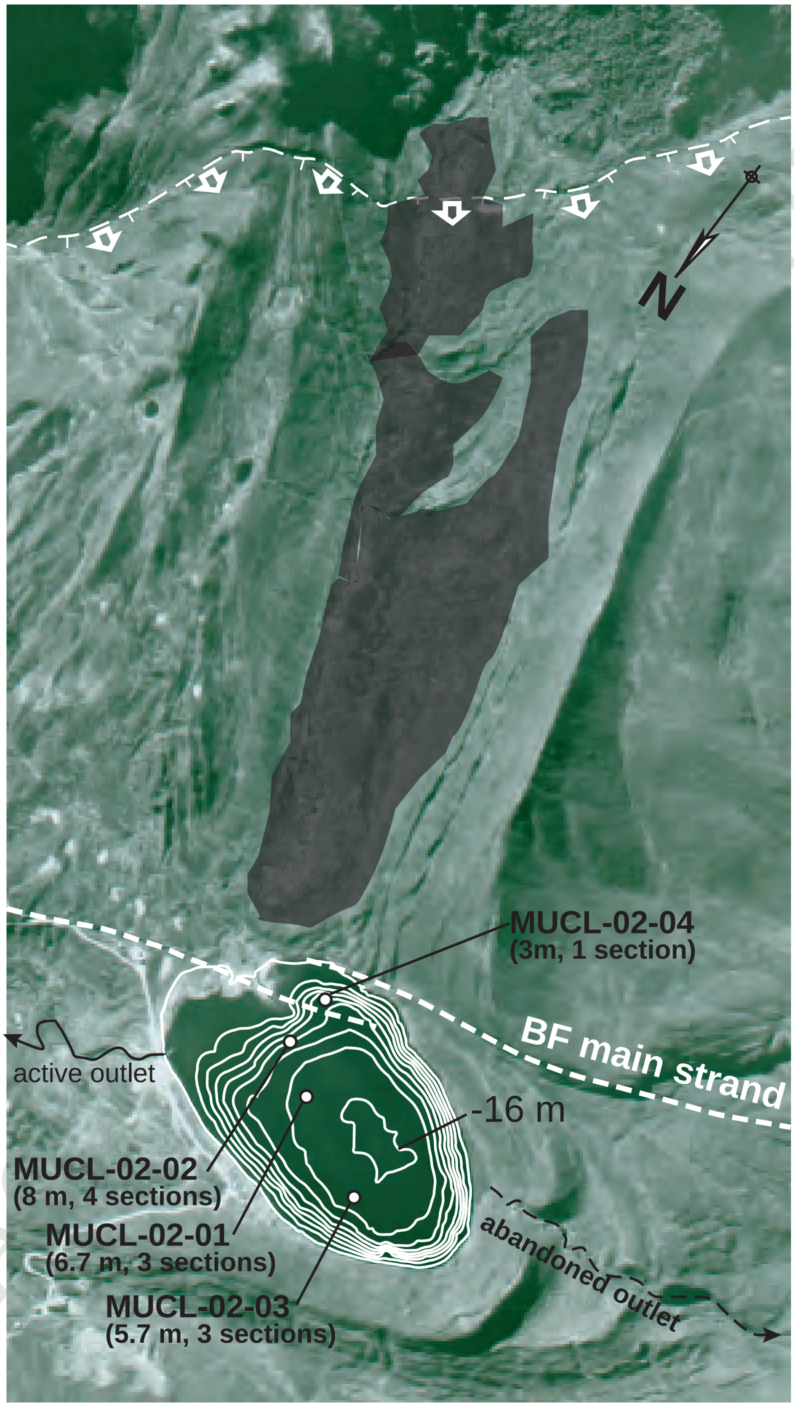


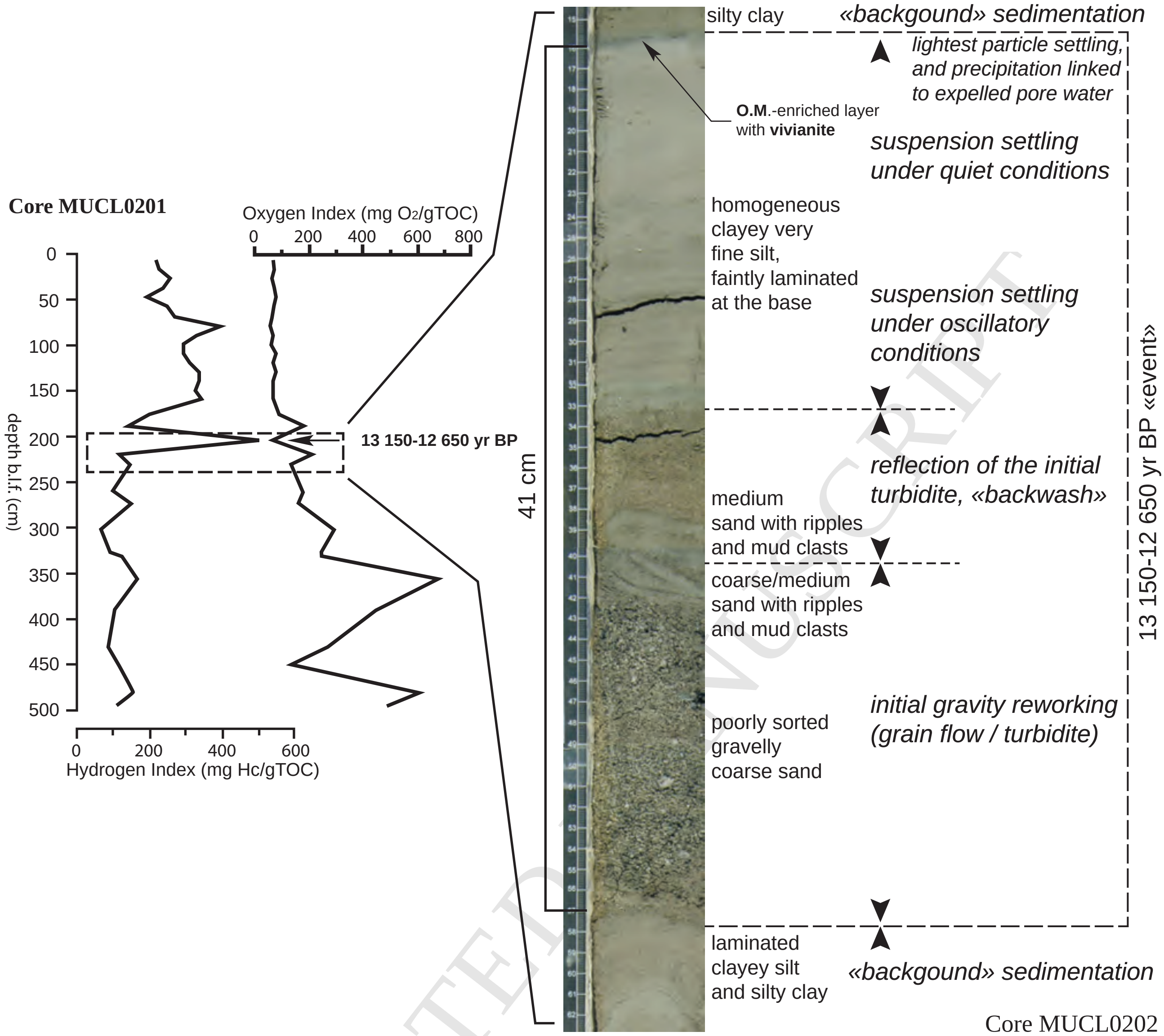
A
A'
A
B
Mesa del Caballo trench
(Audemard et al., 2008)
1 km
N
Los Zerpa Paleo-lake
(Carrillo et al., 2006)
Mucubají Lake
(Carrillo et al., 2008)
main strand
second strand
Morro de Los Hoyos trench
(Audemard et al., 1999)
B'
B



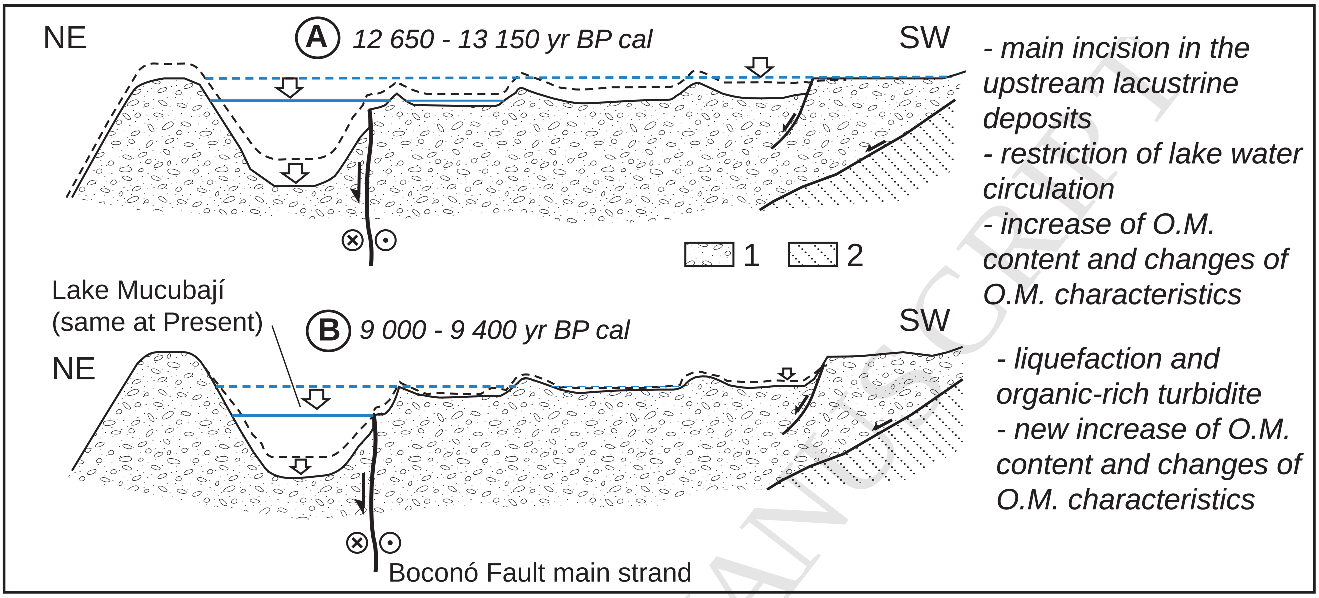
NNW
A'A cross section
SSE
3300 m
3000 m
Los Zerpa
3
2
1
0.5 km
NW
B'B cross section
SE
4000 m
3000 m
Lake Mucubají
lacustrine sediments (outcrops)
1 km
second strand
main strand

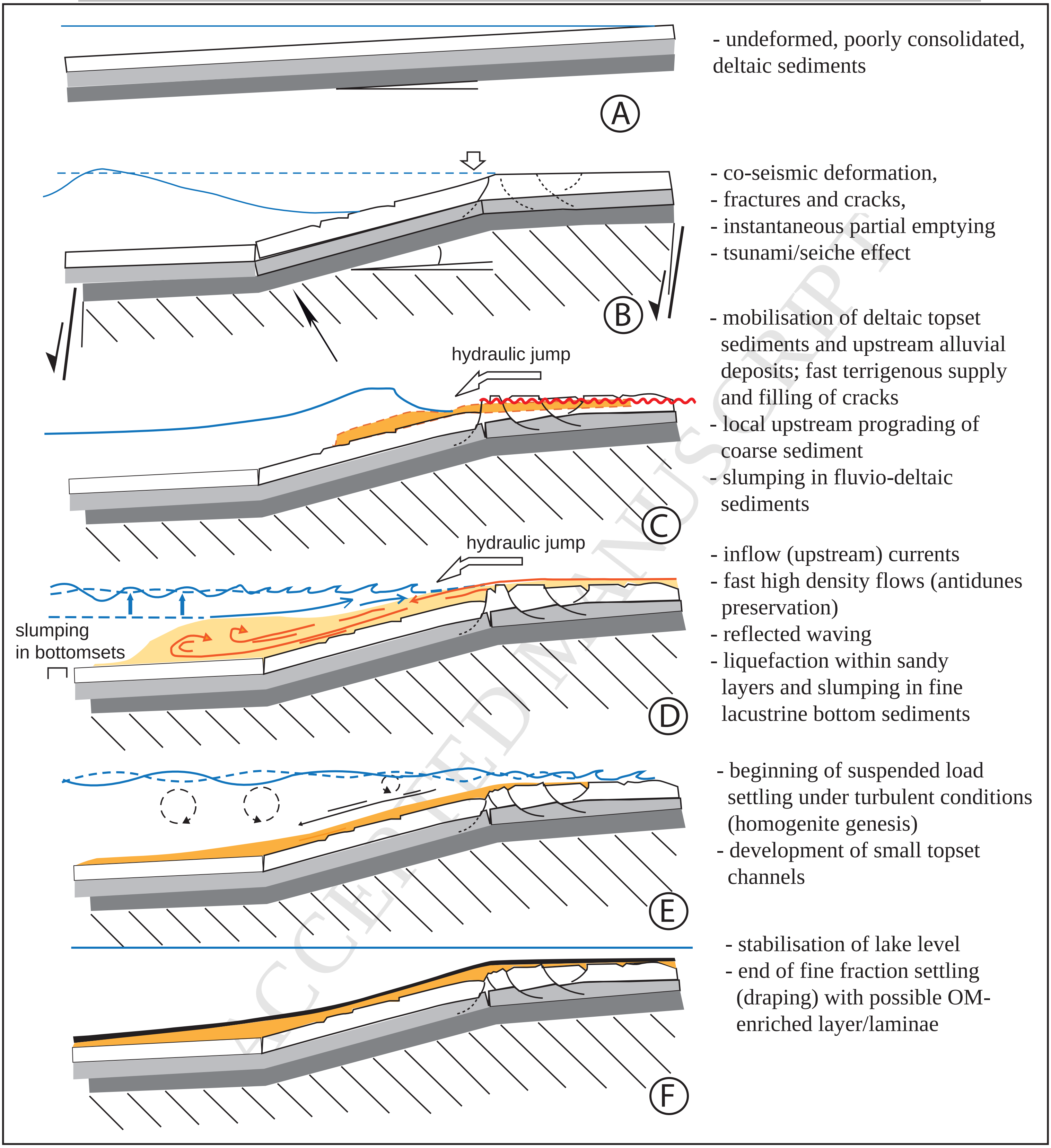

500 m
N
destabilisations within deltaic foresets and topsets
successive imbricated terraces related to emptying events
slumps above liquefied layers within lacustrine bottomsets
specific sedimentary features associated to co-seismic fracturing
sag pond
active outlet
BF main strand
road
abandoned outlets
Santo Domingo R.

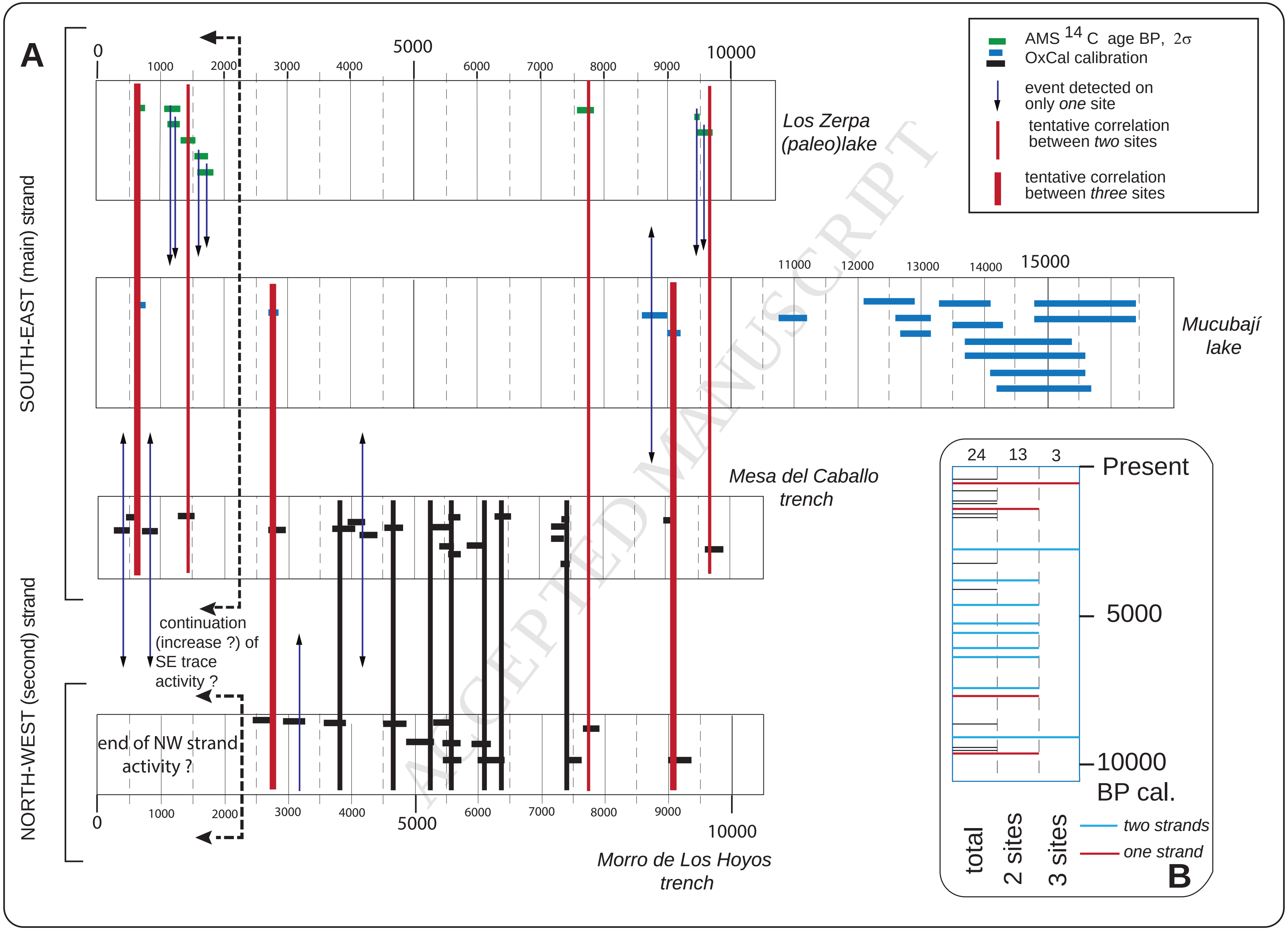

MUCL-02-04
(3m, 1 section)
BF main strand
active outlet
-16 m
MUCL-02-02
(8 m, 4 sections)
MUCL-02-01
(6.7 m, 3 sections)
MUCL-02-03
(5.7 m, 3 sections)
abandoned outlet
N



Core MUCL0201
Oxygen Index (mg O2/gTOC)
0
200
400
600
800
0
50
100
150
200
250
300
350
400
450
500
depth b.l.f. (cm)
13 150-12 650 yr BP
0
200
400
600
Hydrogen Index (mg Hc/gTOC)
41 cm
silty clay
«backgound» sedimentation
lightest particle settling, and precipitation linked to expelled pore water
O.M.-enriched layer with vivianite
suspension settling under quiet conditions
homogeneous clayey very fine silt, faintly laminated at the base
suspension settling under oscillatory conditions
reflection of the initial turbidite, «backwash»
medium sand with ripples and mud clasts
coarse/medium sand with ripples and mud clasts
13 150-12 650 yr BP «event»
initial gravity reworking (grain flow / turbidite)
poorly sorted gravelly coarse sand
laminated clayey silt and silty clay
«backgound» sedimentation
Core MUCL0202


NE
A
12 650 - 13 150 yr BP cal
SW
- main incision in the upstream lacustrine deposits
- restriction of lake water circulation
- increase of O.M. content and changes of O.M. characteristics
1
2
Lake Mucubají (same at Present)
B
9 000 - 9 400 yr BP cal
NE
SW
- liquefaction and organic-rich turbidite
- new increase of O.M. content and changes of O.M. characteristics
Boconó Fault main strand


A
- undeformed, poorly consolidated, deltaic sediments
B
- co-seismic deformation,
- fractures and cracks,
- instantaneous partial emptying
- tsunami/seiche effect
hydraulic jump
C
- mobilisation of deltaic topset sediments and upstream alluvial deposits; fast terrigenous supply and filling of cracks
- local upstream prograding of coarse sediment
- slumping in fluvio-deltaic sediments
hydraulic jump
slumping
in bottomsets
D
- inflow (upstream) currents
- fast high density flows (antidunes preservation)
- reflected waving
- liquefaction within sandy layers and slumping in fine lacustrine bottom sediments
E
- beginning of suspended load settling under turbulent conditions (homogenite genesis)
- development of small topset channels
F
- stabilisation of lake level
- end of fine fraction settling (draping) with possible OM-enriched layer/laminae


A
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Los Zerpa (paleo)lake
11000
12000
13000
14000
15000
Mucubají lake
Mesa del Caballo trench
SOUTH-EAST (main) strand
NORTH-WEST (second) strand
continuation (increase ?) of SE trace activity ?
end of NW strand activity ?
Morro de Los Hoyos trench
AMS 14 C age BP, 2σ
OxCal calibration
event detected on only one site
tentative correlation between two sites
tentative correlation between three sites
24
13
3
Present
5000
10000
BP cal.
total
2 sites
3 sites
two strands
one strand
B

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.