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First paleoseismological results in the epicentral area of the sixteenth century Ameca earthquake, Jalisco – México.

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Abstract: The Trans-Mexican Volcanic Belt (TMVB) is a calc-alkaline volcanic arc cut by different active crustal fault systems that have originated several destructive historical earthquakes. Located in the central part of Mexico this region offers exceptional climatic, and fertility of soil conditions, which is the reason why more than 50% of the Mexican population now live here, increasing the seismic risk. Determining the seismic potential of these fault systems is important in the western section of the TMVB, in the vicinity of the city of Guadalajara, where more than 5 million inhabitants are concentrated in a densely populated urban area.

We focus here on the epicentral area of the M_W 7.2 sixteenth century Ameca earthquake, one of the first earthquakes described to take place in the American continent and which also may be the largest crustal earthquake to have occurred in the TMVB in the historical record. According to some historical sources, this earthquake would be associated with the Ameca-Ahuisculco Fault but no neotectonic study has been carried out so far to characterize this fault. Here, we describe the geomorphology of the fault escarpment and the characteristics of different fault segments. This first step allowed to select a suitable site for a paleoseismological study to track the historic event. The results of the interpretation of

two trenches are consistent, showing evidence of net activity of the fault in the tectono-sedimentary record with two and possibly three seismic events. The older one of these is not well recorded and interpreted as a possible event that could have occurred after 27,91 ± 0,4 cal ka BP and before 5,67 ± 0,064 cal ka BP. The second one and best recorded event occurred around 5,67 ± 0,064 cal ka BP whilst the last one occurred after 0,985 ± 0,065 cal ka BP and is likely to be the geological record of the Ameca sixteenth century earthquake. Considering the potential rupture lengths and the coseismic displacement measured in the trenches, this fault system seems capable of generating earthquakes of magnitude 6.9 to 7.3 and represents a major source of earthquake hazard to the city of Guadalajara.

Keywords: Paleoseismicity, historical seismicity, sixteenth century Ameca earthquake, Trans-Mexican Volcanic Belt, Central Mexico, Seismic hazard.

1-Introduction

Hundreds of potentially active faults intersect the Trans Mexican Volcanic Belt (TMVB), a volcanic arc that crosses central Mexico from the Pacific Ocean to the Gulf of Mexico (Suter et al., 2001; Ferrari et al., 2012). Due to the fertility of its soils and its climate, this intraplate volcanic arc has been particularly attractive to human settlement for thousands of years. Currently, more than half of the Mexican population lives in this geological province where the largest cities of the country are concentrated. The scarcity of studies on the seismogenic potential of these faults puts into question the validity of seismic hazard estimates in the national building rules and regulations (e.g., Instituto Nacional de Electricidad y Energías Limpias, 2017) and other regional bylaws (e.g., Reglamentos construcción México, 2020).

The period covered by the catalog of instrumental seismicity is clearly insufficient to characterize the activity of the slow-moving crustal faults of the TMVB (Zúñiga et al., 2020). However, the historical earthquake catalog (Suárez et al., 2020b), which covers the last 500 years, seems to indicate that many of the fault systems in the TMVB may be active and capable of producing destructive earthquakes with significant damage and loss (Fig. 1; Suárez et al., 2019). Unfortunately, the low slip rates of these faults and long return times

of the major earthquakes that cover hundreds to thousands of years, greatly reduce the time window and make these catalogues of insufficient relevance to evaluate the related hazard.

In such a context, paleoseismological studies have emerged as effective tools for improving the knowledge on the seismogenic potential of faults over a period of several tens of thousands of years. Until now, most of the studies carried out in Mexico have been conducted in the central part of the TMVB, showing that most of the faults of the Morelia-Acambay fault system are active, with recurrence periods for M>6 earthquakes of several thousand years, calculated for individual faults (e.g. Langridge et al., 2000; 2013; Suter 2016; Lacan et al., 2018; Soria-Caballero et al., 2019; Ortuño et al., 2015; 2019). Considering that hundreds of potentially active faults have been identified in the TMVB, it is thus likely that several major earthquakes may occur each century (Suárez et al., 2020a).

One of the first colonial records of crustal earthquakes in the American continent is related to the sixteenth century Ameca earthquake (Fig. 1). On the basis of a compilation of historical documents, Suárez et al., (1994) were able to estimate the intensity values, calculate a magnitude between 7 and 7.8 and establish the location of the epicenter on the faults bordering the Jalisco block, to the southwest of Guadalajara. More recently, using the same documents as Suárez et al. (1994) and a historical document called "Relación de Ameca", Suter (2015; 2019) suggested the earthquake occurred on the Ameca-San Marcos normal fault system, whose complete rupture length can be empirically related to a magnitude of 7.2 ± 0.3.

Considering the work cited above and the fact that the geomorphological expressions of the fault escarpments indicate a possible persistent tectonic activity (Castillo et al., 2014), this fault system could represent a major hazard for the region. As a contribution to the geological characterization of this seismogenic fault, we present here the first paleoseismological study in the western part of the TMVB with the focus on the prehistoric seismic activity of the Ameca-Ahuisculco fault (AAF), the northernmost fault of the Ameca-San Marcos fault system. To do so, detailed geomorphological mapping of faults in the region was conducted with the aim to identify a site having suitable conditions for the preservation of the sedimentary record of earthquakes. Two trenches were dug and the units displaced by faults were sampled for radiocarbon dating, to infer the paleochronology of surface ruptures recorded. The scope of this study covers the assessment of the occurrence

of potentially large earthquakes on this well-defined fault segment of the AAF during historical and pre-historical times to quantify their number, magnitudes and recurrence times. This works represents the first step of a long-term effort to assess the seismic hazard of low slip rate active faults in the vicinity of the megacity of Guadalajara.

2- Seismotectonic setting

2.1 The Ameca–Ahuisculco fault in the Trans Mexican Volcanic Belt

The tectonically active crustal structures of the TMVB are distributed in an arrangement of segmented normal fault systems spread over 900 km between, the Gulf of Mexico and the Pacific coast (Fig.1; Ferrari et al., 2012 and references therein). These fault systems are mainly east-west oriented in the central TMVB, while the Tepic-Zacoalco and Colima fault systems, on the western TMVB, show respective NW-SE and N-S orientations, bordering the Jalisco Block (Fig. 1). South of Guadalajara, the intersection between the Chapala, Tepic-Zacoalco and Colima fault systems forms the triple-junction of Guadalajara (Fig. 1). The studied area is located in the Tepic-Zacoalco fault system (TZFS) near the triple-junction mentioned above. The TZFS extends over a distance of 250 km, forming the north-east boundary of the Jalisco Block (Fig. 1; Allan, 1986). The TZFS is made up of different fault subsystem expressed as grabens and half-graben, mainly formed between the late Miocene and the Quaternary (Ferrari and Rosas-Elguera, 2000). The extension across the TZFS is constrained by GPS measurement to be ≤8 mm/year (Selvans et al., 2011) that could result in an earthquake recurrence time of 1,250 years for this fault system (Suárez et al., 2019). At the southeastern end of the TZFS, the Ameca-Ahuisculco fault, consists of a ~55 km network of south dipping normal fault segments delimiting the plutonic to volcanic basement north of the fluvio-lacustrine filling of the Ameca valley to the south (Rosas-Elguera et al, 1997; Ferrari and Rosas-Elguera, 2000; Fig. 2).

2.2 The sixteenth century Ameca earthquake

The instrumental seismic catalogue does not show clear evidence of micro- or macroseismicity related to the AAF (Zúñiga et al., 2020). On the other hand, studies of historical seismicity by Suárez et al., (1994, 2020a) highlight the occurrence of a significant earthquake (M 7-7.8) which affected the area in 1568 and caused major destruction in the villages and towns located near to the faults bordering the Jalisco block, along the Tepic-Zacoalco and Colima fault systems. More recently, mainly based on descriptions of the 1579's colonial document called "*Relación de Ameca*" (Acuña, 1988), Suter (2015; 2019) identified the AAF as well as the Villa Corona and the San Marcos Faults as the rupturing faults, responsible for the earthquake (Fig. 1B). Along these fault systems, Suter (2015) calculated a 54-59 km long surface rupture and a scarp of 1,67 to 3,34 m associated with the event. Suárez et al. (2019) estimated a magnitude of 7.2 ± 0.2 for this earthquake based on the inversion of intensity data, making it the strongest known cortical earthquake in central México. Suter (2015) also reevaluate the date of the earthquake to 1567; however, the inconsistencies between historical documents, possibly linked to the passage from the Julian to the Gregorian calendar between the dates of occurrence of the earthquake and the drafting of the documents describing it, do not allow to close the debate about the exact date of the earthquake that will therefore be referred to as the sixteenth century Ameca earthquake in this study (Suárez et al., 1994; 2019; 2020a; Suter 2020).

3- Methods

A geomorphological study of the AAF has been carried out in order to precise the geometry, length and segmentation of the fault and identify the optimal site for the excavation of paleoseismic trenches. The recompilation of the available bibliographic documents as well as geological maps on a scale of 1:50,000 allowed us to trace a first approximation of the fault system and to identify uncertainties in its geometry. After that, the study of digital elevation models of different resolutions, available on the websites of the National Institute of Statistics and Geography (INEGI) or Japanese Space Agency (ALOS satellite, 12 m resolution) as well as the study of the aerial photographs available, allowed us to map the geometry and segments of the AAF. On this basis, different potential

trench sites were identified. The optimal sites for paleoseismic trenching were decided conducting a field survey.

During February 2019, two trenches (Buenavista 1 and 2) were excavated with a backhoe excavator, perpendicularly to the inferred fault trace. Excavations were between 12 and 16 meters long and 2 meters deep, exposing the moderately preserved fault scarp. Following classical methods for paleoseismic survey across normal faults (McCalpin, 2009) the trench walls were gridded (1m x 0,5 m) and logged. The photomosaics of the walls are available in the supplemental material. Three samples of paleosols (Bulk) were taken from the west wall of Buenavista 1 trench and processed by the LMC14-CEA Saclay laboratory, GIF sur Yvette, France. Radiocarbon ages were calibrated using the OxCal 4.3 program (Bronk Ramsey, 2009) and expressed in calibrated years before present (cal. BP).

4- Geomorphology of the Ameca-Ahuisculco fault

The AAF extends WNW-ESE to NW-SE, nearly 55 km from the Ameca range to the southern end of the Ahuisculco range (Fig. 2). It constitutes the NNE boundary of the Ameca half-graben (Rosas-Elguera et al, 1997). According to our analysis, the AAF can be divided into three main fault segments based on its morphology; the western, central and southeastern AAF.

The western AAF (1 in Fig. 2A) comprises four overlapping branches with different orientations that separate the Ameca range, mainly composed of competent plutonic and andesitic to basaltic volcanic rocks, from the Ameca alluvial plain. Two WNW-ESE oriented main branches cut the topography of the southern flank of the Sierra Ameca by a 50 to 90 m high escarpment (1a and 1d in Fig. 2A). The branch 1a is 4 km long next to the Ameca range and possibly extends up to 10 km westward, considering that it may continue into the alluvial plain (Yánez Mondragón y Rosales Gómez, 2005). The 1d strand extends 20 km and its escarpment height varies between 40 and 90 m, showing triangular facets, while the total height of the mountain front reaches 1000 m above the plain. These two main branches of similar orientation and height are connected by two smaller NE-SW and E-W oriented strands (1b and 1c in Fig. 2A). Branch 1b is 5 km long and displaces the topography by a 10 to 20 m escarpments, 1c is located in the down-thrown block controlled

by 1d. It is 7 km in length and displaces the alluvial fans that come down from the Ameca range by 2 to 5 m. This last strand appears to be more recent than the others and, its orientation suggests a new stage in the growth of the fault system.

The central AAF segment (2 in Fig. 2A) is made up of different branches having the same orientation and the same SSW dip direction as the western segment. There is no clear separation between these two segments but more of a morphological break, the first segment corresponding to the southern border of the Ameca range. For the second segment, the main strand is 17 km in length with a scarp height that varies from 2-6 m in the alluvial valley floor of the Ameca River to 10-35 m in the pyroclastic flows of the northern Ahuisculco range. North of this main fault branch, there are three small strands of 3 to 10 km length, with scarp heights that vary between 3 and 15 m, affecting the pyroclastic flows of Ahuisculco range.

The southeastern AAF segment is 14 km long (3 in Fig. 2A) and conforms the southwestern edge of the Ahuisculco range. Its NW-SE orientation forms an angle of ~ 40° with the fault segments described above, and could correspond to a transitional zone between the Tepic-Zacoalco and the Colima fault system. There is no clear geomorphic segmentation between the central and southeastern segments which present a topographic escarpment varying between 50 and 100 m. Their distinction is mainly related to their difference in orientation.

Trench site location

The western and southeastern AAF segments (1 and 3 in Fig. 2A) present relatively high scarps and are, therefore, unlikely to have preserved recent sedimentary units affected by the fault. In contrast, the central segment (2 in Fig. 2A) affects a relatively flat area between the Ameca and the Ahuisculco mountain ranges where the sedimentary record of earthquakes is more likely to have been preserved. An ideal site would have been within the intersection of the alluvial plain of the Ameca river and the central fault scarp. Unfortunately, an irrigation channel was built at the foot of the escarpment, destroying potential markers of past tectonic activity of the fault (Fig. 3A). In the central part of the fault segment, near to Buenavista village (< 2km, Fig. 3A), the fault scarp can be easily observed; it is relatively low (5 to 10 m) and is not affected by human activity, other than

agriculture (Fig. 3B and C). In the field, the fault trace can be followed and traced using the changes in vegetation related to the composition and changes in the permeability of the basement rocks (Figs. 3D, E and F). Additionally, logistical factors such as easy access and authorization to dig trenches were determining for the selection of the study site. With the help of a backhoe, Buenavista 1 and 2 trenches, 16 and 12 meters long respectively, were excavated 20 m from each other, perpendicular to the fault trace.

5 Paleoseismic Trenching

5.1 Trench stratigraphy

At Buenavista site, the fault separates the volcanic rocks of the Ahuisculco range from the sedimentary rocks of the Ameca alluvial plain. Buenavista 1 and 2 trenches expose a volcano-sedimentary sequence consisting of 7 units named A to G from younger to older (Fig. 4). These units are easily correlated between the two trenches and described in detail in Table 1. Three samples were taken in the western wall of Buenavista 1 trench of units F, E and B for radiocarbon dating.

At the bottom of the trenches, Unit G (UG) is interpreted as a pyroclastic flow composed of up to 60 cm diameter sub-angular blocks of andesitic to dacitic composition. This unit is only visible in the up-thrown block where it is barely covered by the current soil (Unit A) at the two trenches (Fig. 4).

In the downthrown block the same 5 units are observed in the two trenches. At the bottom, unit F (UF) is a colluvial unit composed of a chaotic accumulation of blocks of different compositions embedded in a heterogeneous matrix composed of reworked and mixed paleosols and very fine ashy deposits. Despite the fact that only the upper part of this unit is observed in the 2 trenches, its geometry and its chaotic organization suggest that it is likely to be a colluvial wedge related to a surface rupture. The dating of a bulk soil sample taken from the matrix of this unit indicates an age of 27.909 ± 400 cal a BP (Table 2). Considering that the sample corresponds to a paleosol that has been reworked during the formation of UF, this age should be considered as prior to the formation of the wedge, that

is: prior to the earthquake. This unit in turn is covered by UE, an alternation of 10 to 20 centimeters thick fine ashy deposits separated by some paleosol layers indicating relatively long periods between the different ash deposits (Fig. 4). A bulk soil sample taken from the thickest paleosol subunit gives an age of 5670 ± 64 cal a BP (Table 2). Next to the fault, UE is overlain by UD. Made up of angular to sub-angular blocks with a chaotic arrangement, UD has a characteristic wedge shape, whereby is interpreted as a colluvial wedge (Fig. 4) resulting from the erosion of the scarp formed during a surface rupturing earthquake, as observed in other case studies carried out in the region (Langridge et al., 2013; Sunyé-Puchol et al., 2015). Partially covering the wedge and UE, UC is formed by blocks in a clay matrix and interpreted as a slope deposit. On top of it, UB is composed of fine re-sedimented ash-fall deposit intercalated with clayish carbon rich paleosols. The dating of a bulk sample taken from one of these paleosols gives an age of 985 ± 65 cal a BP (Fig. 4 and Table 2). At the uppermost part, UA is rich in organic matter and corresponds to the present-day soil covering the surface on both sides of the fault.

5.2 Faulting history

The faulting geometry is almost the same in the four walls (Fig. 4). A 70 to 80º south dipping main fault with an E-W strike separates the volcanic basement, to the north, from the late Pleistocene to Holocene sedimentary filling to the south. UA is the only unit preserved on both sides of the fault and does not present any deformation of tectonic origin. UB and UC are poorly preserved above the fault zone, but the displacement of unit B by a secondary synthetic fault is visible in trench 1-W. All the units deposited before UC are more clearly affected by faulting. Unfortunately, as most of the units are not preserved on either side of the main fault, it is not possible to determine the number of events and the associated displacements by measuring the displacement of the sedimentary units. However, the presence of synthetic and antithetic structures to the main fault affecting different units and the preservation of colluvial wedges allows the identification of different paleoseismic events.

The most recent event (Ev. 3) can be identified on the walls of the two trenches, where antithetic and synthetic faults to the main one are cutting UD. In the western wall of trench

1 the F3 faults not only intersect UD but also UB, which is locally better preserved (Fig. 4). However, the poor preservation of the units does not allow us to measure the coseismic displacement related to this event. The previous event (Ev. 2) corresponds to relatively large displacement along the main fault and to the formation of colluvial wedge 2 (UD). Before this, the older event recorded in the trench (Ev. 1) is represented by colluvial wedge 1 (UF). Since the wedge is not completely exposed, we cannot estimate the slip per event. Ev. 2 occurred contemporary or shortly before the formation of UD and Ev. 1 contemporary or shortly before the formation of UF. Note that UF, being only partially visible in the trenches, makes its interpretation as a colluvial wedge uncertain. Thus, this event is considered as hypothetical in the discussion chapter.

6. Discussion

6.1 Retrodeformation and chronology of the paleoseismic events

Based on the information collected in the Buenavista 1 and 2 trenches, two and possibly three paleoseismic events are interpreted. Through a retrodeformation analysis, the proposed sequence of rupturing and sedimentary events is summarized graphically. The tectono-sedimentary evolution of the trench can be divided into 5 main stages (Fig. 5):

1. During or shortly after a first seismic event (Ev. 1) associated with a surface rupture, the fault scarp is partially eroded and a colluvial wedge is formed at its base. Considering empirical relationship proposed by McCalpin (2009) to estimate the size of the coseismic escarpment from the thickness of the colluvial wedge near the fault (> 40 cm), the topographic escarpment caused by the earthquake was likely greater than 80 cm. This first paleoseismic event has significant uncertainty since only the upper part of UF is visible in the trench and this unit could be interpreted differently. The dating of a bulk sample taken from a reworked paleosol indicates that UF was formed after 27.909 ± 400 cal a BP (Table 2).

2. After its formation, the colluvial wedge (UF) is eroded, reshaped and it is covered by deposits of ash interspersed with soils formed during periods of less volcanic activity (UE).

A bulk sample taken from the thickest paleosol gives an age of 5670 ± 64 cal a BP for UE (Table 2).

3. A second earthquake (Ev. 2) with an approximate vertical displacement of 134 to 180 cm occurs a shortly after 5670 ± 64 cal a BP. This displacement is calculated based on the 67 to 90 cm thickness of the colluvial wedge formed by erosion of the scarp after the earthquake.

4. The erosion of the upper part of the relief causes the formation of slope deposits (UC) filling the depression formed at the toe of the scarp. All these previous units in turn are covered by an alternation of ash and soils (UB). A bulk sample taken from one of the paleosols gives an age of 985 ± 65 cal a BP for UB (Table 2).

5. Between the formation of UB and UA another earthquake (Ev. 3) must have occurred affecting UD and UB (only preserved above the fault zone in the 1 W trench).

6. Finally, the last stage corresponds to the current state in which UA, the current soil, covers all the units mentioned above.

Despite incomplete preservation of the tectono-sedimentary record and only few age datings in the Buenavista trenches, the age of the different seismic events is partially constrained. Ev. 1 is more hypothetical and we only know that it occurred after 27,91 ± 0,4 cal ka BP and before 5,67 ± 0,64 cal ka BP. Ev. 2 took place 5,67 ± 0,64 cal ka BP ago while the last earthquake, Ev. 3, occurred after 0,985 ± 0,065 cal ka BP and probably correspond to the sixteenth century Ameca earthquake.

6.2 *Estimation of paleomagnitudes*

The estimate of a paleoseismic event magnitude is a crucial factor in the evaluation of the seismic hazard (Reiter, 1988). Different empirical relationships can be used in order to estimate paleomagnitudes from parameters such as surface rupture length (SRL) or vertical

displacement (Dv). According to Stirling et al. (2013), who compiled and reviewed these scaling relationships based on their relevance in a specific tectonic regime (e.g., plate tectonic setting, fault slip type, seismogenic thickness, lithology), the relationships proposed by Wells & Coppersmith (1994) and Wesnousky (2008) are the most suitable in our case and will be used subsequently.

Since only the vertical displacement associated with event 2 is adequately constrained, the Dv related with this event will be used in order to estimate a paleomagnitude along this fault (average observed displacement: 1.65 m, maximum observed displacement: 1.80 m). The results obtained from the empirical relations should be considered an approximation given that recent surface rupture shows great variability of vertical surface displacement along the scarp and accordingly, the poor representativity of isolated coseismic displacements measured at a given site along the scarp (Rockwell and Ben-Zion, 2007; Fletcher et al., 2014; 2020; Ritz et al., 2020). On the other hand, considering the complexity of the fault system, it is not possible to estimate, with only one trench site, if only one fault segment, the entire fault or various faults of the fault system ruptured during an event. In order to consider these unknowns, different scenarios of surface rupture length (SRL) must be considered (Fig. 6). The first one (sc. A) involves only part of the western segment and the totality of the central segment of the AAF with a total length of 35 km. Scenario B corresponds to a rupture length of 55 km along almost the whole AAF and scenario C to 70 km length rupture involving three segments of the Ameca - San Marcos Fault System (Fig. 6). This last scenario corresponds to the rupture suggested by Suter (2015) based on the historical description in the "*Relación de Ameca*". The results of the paleomagnitude estimations for each scenario are summarized in Table 3. Following Suter (2015), the westernmost branches of the AAF were not considered in the rupture scenarios. However, due to their short length, their inclusion or exclusion in the calculation of the possible magnitude has an influence of less than one tenth.

The magnitudes calculated from the SRL relations range between $6.8 \pm 0.3 \leq Mw \leq 7.3 \pm 0.3$, while the one calculated from the maximum vertical displacement measured in the trench is 6.9 ± 0.1. All these results are of the same order of magnitude and indicate that major prehistoric seismic events occurred along this fault long before the sixteenth century Ameca earthquake. Nowadays, considering the high population density in the area, an

earthquake of this magnitude could have disastrous consequences in terms of destruction and social impact.

6.3 The sixteenth century Ameca earthquake and the regional seismic hazard

This study provides geological evidence of recent seismotectonic activity along the AAF, which has generated at least two major earthquakes in the last 5000 years. The age of the last earthquake recorded in the trenches is not well constrained but probably corresponds to the historical Ameca earthquake. Based on historical documents, Suter (2015) describes the Ameca earthquake as a 54-59 km-long rupture with associated vertical displacement between 1.67 and 3.34 m-high along the mountain front that separates the Ameca range from the plain (Fig. 6). Unfortunately, the displacement associated with this earthquake is not measurable in the trenches and the length of the surface rupture cannot be evaluated with the information reported at only one site.

These preliminary results attest to the persistent seismic activity of the fault system by geological means, providing a first estimate of paleomagnitudes and the paleo-earthquake chronology in the region. However, more trenches are necessary to confirm and complete the historical descriptions and interpretations of the Ameca earthquake. More paleoseismological studies will also clarify the relationship between the different fault segments and the possibility of multifault rupture events. The sedimentary record of surface ruptures reported here leads to estimates of a magnitude close to 7.0 for these events. According to data from the Institute of Statistical and Geographical Information (IIEG) of the Jalisco government, in 2017 more than 5 million people lived in the megacity of Guadalajara, within a radius of 60 km from the AAF. Considering the important growth of the population and the poor-quality of the infrastructures, the hypothesis of a crustal earthquake with a magnitude ~ 7.0 would have catastrophic consequences. Although the probability of occurrence of such an event is low compared to a subduction earthquake, the expected damage could be comparable or greater; its shallow focal depth and its proximity to inhabited areas reduce the effectiveness of potential seismic early warning systems. Moreover, historical or early instrumental events such as the 1920 Jalapa earthquake shows that even earthquakes of moderate magnitudes, statistically more frequent, can have equally

disastrous consequences. Indeed, with only Mw 6.4, the Jalapa earthquake is the second deadliest earthquake in Mexico, only behind the 1985 subduction event (Suárez and Novelo-Casanova, 2018).

Accordingly, it is necessary to consider such shallow crustal sources in the seismic hazard evaluations in Mexico, as well as its implications for earthquake-resistant construction standards for the entire area affected by these faults.

In terms of interpretation of paleoseismic data, the increasing number of paleoseismological studies in the TMBV show the importance of working at the scale of the entire fault system to evaluate the seismic hazard. Indeed, the only two known historical events presenting associated surface ruptures in the TMVB correspond to complex multifault rupture events with associated magnitudes of 6.9 and 7.2 (e.g. The sixteenth century Ameca and the Acambay 1912 earthquakes; Suárez et al., 1994; Suter et al., 1995; Suter 2015). Ignoring the possibility of a multi-fault rupturing event, the magnitude of potential earthquakes could be greatly underestimated considering that the longest faults in the TMVB rarely reach 50 km. In such a context, the number of trench sites relatively to the size and the complexity of the fault system should be better taken into account in the recently increasing number of proposals for estimating the paleoseismological uncertainty (e.g. Atakan et al., 2000; Rodriguez-Perez et al., 2017).

Conclusions

In slow deforming regions where faults slip rates are of the order of or below 1 mm yr−1, earthquake recurrence intervals can reach thousands of years. For such low rates of deformation, geodetic techniques are usually not capable of detecting tectonic movements. The time period covered by instrumental seismicity is not sufficient neither to describe the fault behavior nor to confidently estimate maximum magnitudes or fault segments involved. Still in many regions of the world, especially where long written records do exist, historical sources can significantly extend the knowledge on past seismicity and potential seismic sources. As a first result, two paleoseismic trenches excavated in the central segment of the Ameca-Ahuisculco fault, show evidence of its Holocene activity with two and possibly three paleo-earthquake ruptures. The older and less clearly defined recorded

event, interpreted as a possible event, occurred after 27,91 ± 0,4 cal ka BP and before 5,67 ± 0,064 cal ka BP. The second one and best recorded occurred around 5,67 ± 0,064 cal ka BP and the last one occurred after 0,985 ± 0,065 cal ka BP and could correspond to the rupture of the sixteenth century Ameca earthquake.

Based on the vertical coseismic displacement calculated for the second event (180 cm), and different surface rupture length scenarios, maximum paleomagnitudes of 6.9 to 7.3 are estimated. This study presents preliminary but important results and underlines the difficulty of evaluating the size and length of a surface rupture and, the need of performing a more comprehensive paleoseismological studies on this complex and extensive fault systems.

Considering the estimated magnitudes and the complexity of the fault system, the Ameca-Ahuisculco fault is an important seismic source of the TMVB, capable of generating destructive earthquakes with magnitudes ~ 7. Although the frequency of occurrence of large crustal earthquakes is low compared with subduction earthquakes, such a possibility has to be considered in seismic hazard assessment in central Mexico region, where most of the Mexican population is concentrated. Therefore, it is particularly important to better evaluate the possibility of occurrence of multifault rupture events within the TMVB by increasing the number of paleoseismological studies.

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Figure Captions:

Figure 1. (A) Main tectonic features and historical seismicity Map of the TMVB. Black lines indicate different fault systems and the red stars the main historical seismic events (Modified from Suárez et al., 2019 and Zúñiga et al., 2020). (B) Zoom on the Ameca-San Marcos Fault System. The red lines represent the faults that presumably ruptured during the sixteenth century Ameca earthquake according to Suter (2015).

Figure 2. (A) Morphological map of the Ameca-Ahuisculco fault system. The colored numbers represent the scarp heights (in meters) measured in each sub-segment. (B) Geological map of the same area showing the rocks affected by the fault (modified from Ferrari et al., 2018).

Figure 3. (A, B, C) Aerial photograph of the AAF near the Buenavista trench site (from Google Earth). The insets in A and B correspond to areas shown in B and C.

Figure 3 (continued). (D) 3D view of the escarpment at Buenavista trench site (from Google Earth), (E, F) field photographs of the trenches showing the difference of vegetation on both side of the fault.

Figure 4. Logs of the Buena vista trenches. See Table 1 and text for the description of the units. Eastern walls of the trenches are flipped for ease of comparison. At the bottom, zoom of the fault zone of the trench 1-W. Photomosaics in supplementary material.

Figure 5. Retrodeformation analysis showing the main tectono-sedimentary stages recognized in Buenavista trenches.

Figure 6. Rupture scenarios proposed for estimate the paleomagnitudes. WAAF: Western Ameca-Ahuisculco Fault, CAAF: Central Ameca-Ahuisculco Fault, EAAF: Eastern Ameca-Ahuisculco Fault, VCF: Villa Corona Fault, SMF: San Marcos Fault. In red: rupturing fault, in yellow: non-rupturing fault.

Supplementary material: Photomosaics of the walls of the Buena vista trenches (see figure 4 for interpretation).

Table captions

Table 1: Sedimentary description and genetic interpretation of units exposed in the trench walls.

Table 2: Dating results. Samples processed by the LMC14-CEA Saclay laboratory, GIF sur Yvette, France. The calibrated ages have been obtained using OxCal 4.2 software (Bronk Ramsey, 2009).

Table 3: Magnitudes calculated with the empirical relationships of Wells & Coppersmith (1994) and Wesnousky (2008)

UNIT	DESCRIPTION	INTERPRETATION
UA	Dark brown clay with abundant organic matter. Thickness from 40 to 53 cm. Some andesitic to dacitic sub-rounded clasts are dispersed without any particular organization.	Current soil
UB	38 to 80 cm of alternation of light ashy layers with brown and orange tones and dark clay layers. The ashy layers are characterized by the presence of lithics with a high degree of weathering and clay minerals due to the alteration of plagioclase. Lithics are sub-rounded to subangular with sizes ranging from 7 mm to 6 cm. The iron oxides and mafic minerals are present in a smaller proportion. The brown clay layers is carbon rich and reaches 8 cm thick.	Re-sedimented ash fall deposit interspersed with layers of paleosols
UC	Mainly andesitic clasts with different degrees of alteration and oxidation in a dark clay aphanitic matrix. The clasts are subangular to subrounded in shape with poor classification and variable size between 2 and 60 cm. The unit's thickness varies from 12 to 52 cm.	Slope deposits
UD	Mainly subangular andesitic clasts and blocs without preferential direction in a fine size sandy to clayey matrix. This unit draws a wedge shape, thick near the fault plane and thinner further.	Colluvial wedge 2
UE	22 to 75 cm of alternation of yellow ashy layers and dark-brown clay layers. Some millimetric to centimetric mafic clasts and obsidians are scattered in the ashes. They are smaller towards the top and larger towards base. The clay layer reaches 14 cm thick.	Ash fall deposit with an intermediate paleosol
UF	32 cm of angular clasts of varied composition, poorly classified, with a chaotic disposition and violet hue due to oxidation in a brown to orange matrix. This last is quite heterogeneous and relatively consolidated in some part.	Colluvial wedge 1
UG	Located in the footwall of the two trenches, this unit consist in andesitic to dacitic blocks of any size embedded in a hardened and weathered ashy matrix with dark yellow to orange hue, rich in quartz and in products of alteration of plagioclase, which increase when approaching the fault plane.	Pyroclastic flow of blocks and ash

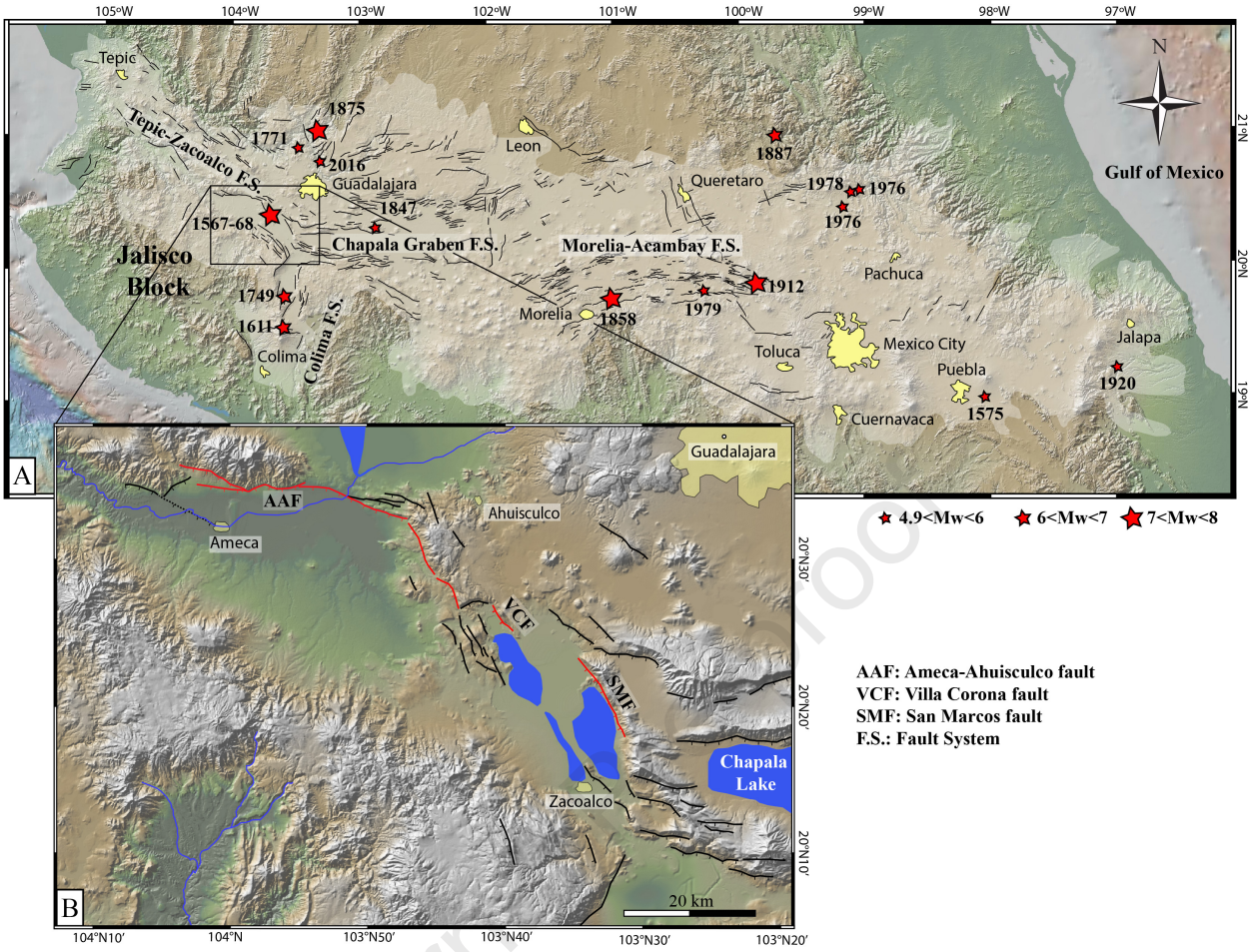
Table 1: Sedimentary description and genetic interpretation of units exposed in the trench walls.

Sample name (Unit)	Type of sample	Radiocarbon age (yr BP)	Calibrated age	Calibrated age (Yr. Cal. BP)
TBV-M-5 (UB)	Soil (Bulk)	1045 ± 30	965 ± 65 cal. AD	985 ± 65
TBV-M-4 (UE)	Soil (Bulk)	4950 ± 30	3721 ± 64 cal. BC	5670 ± 64
TBV-M-3 (UF)	Soil (Bulk)	23750 ± 210	25960 ± 400 cal. BC	27909 ± 400

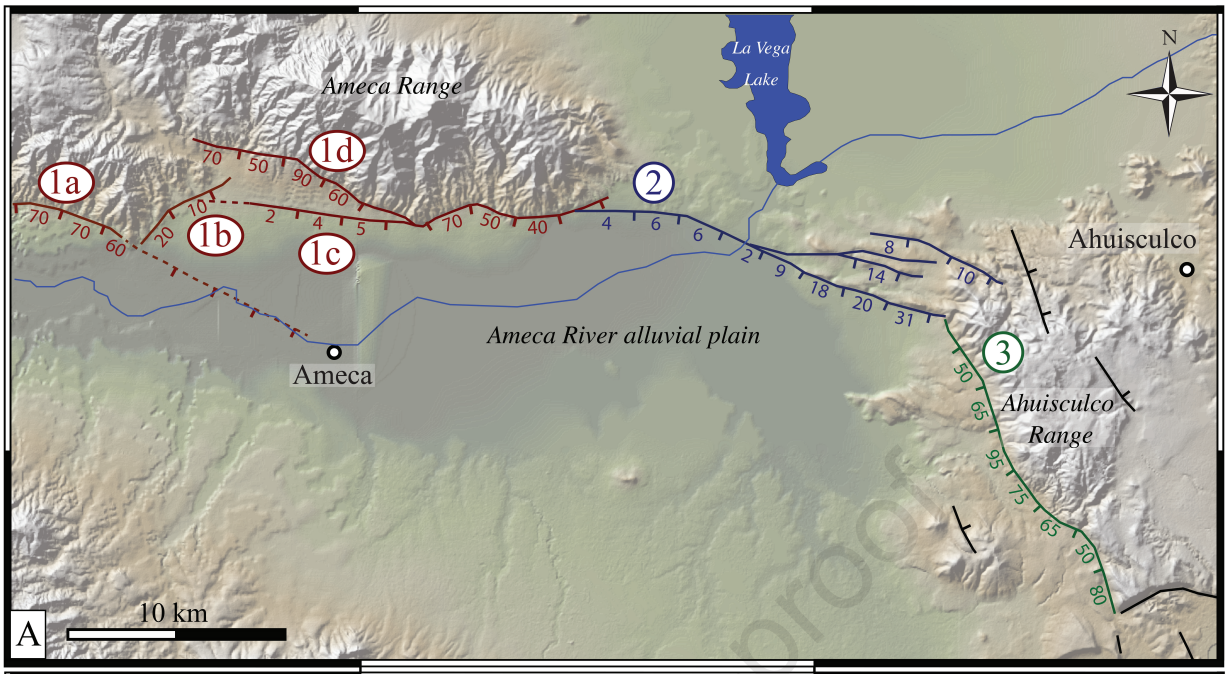
Table 2: Dating results. Samples processed by the LMC14-CEA Saclay laboratory, GIF sur Yvette, France. The calibrated ages have been obtained using OxCal 4.2 software (Bronk Ramsey, 2009).

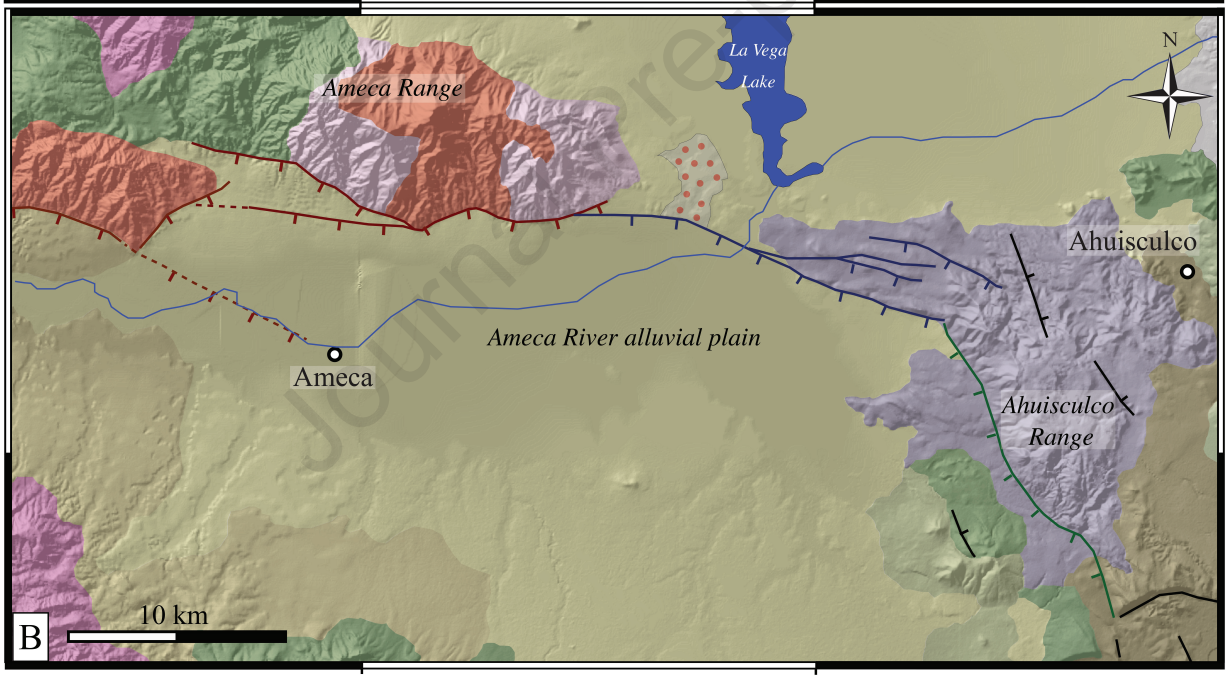
				Wells & Coppersmith (1994)		Wesnousky (2008)
STAGE	**SRL (km)**	**D_{max} (m)**	**D_{prom} (m)**	**Mw (SRL)**	**Mw (D_{max})**	**Mw (SRL)**
A	35	1.80	1.65	6,9 ± 0.3	6,9 ± 0.1	6,8 ± 0.27
B	55			7,1 ± 0.3		6,9 ± 0.27
C	70			7,3 ± 0.3		7,0 ± 0.27

Table 3: Magnitudes calculated with the empirical relationships of Wells & Coppersmith (1994) and Wesnousky (2008).



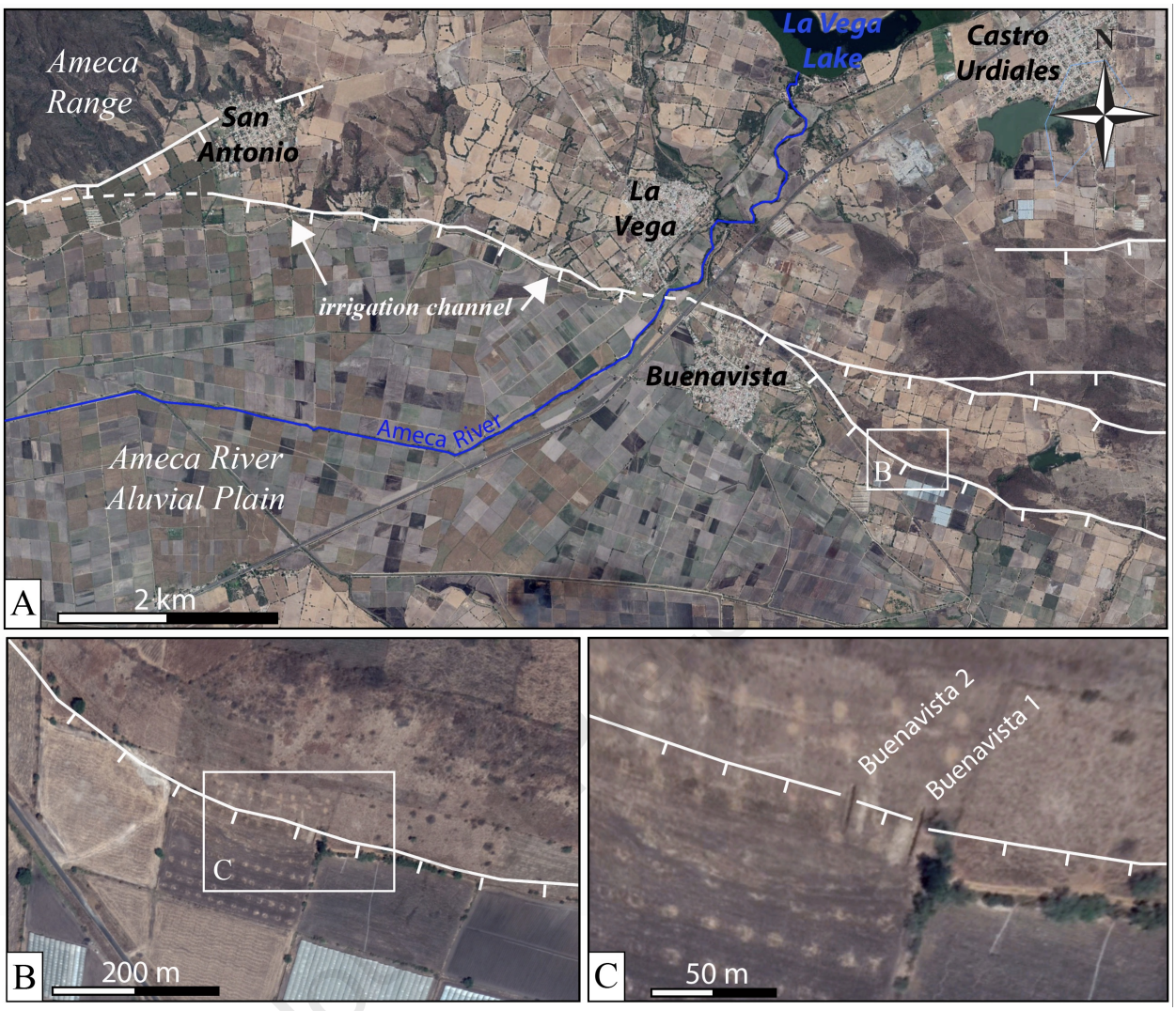
AAF: Ameca-Ahuisculco fault
VCF: Villa Corona fault
SMF: San Marcos fault
F.S.: Fault System





LEGEND

- Inconsolidated recent sediments (Quaternary)
- Volcano-sedimentary and lacustrine deposits (Late Miocene to Pleistocene)
- Silicic domes and minor ignimbrites (Middle Pleistocene to Holocene)
- Silicic pyroclastic flows and fall deposits (Middle Pleistocene to Holocene)
- Monogenetic cones and associates lava flows (Late Pliocene to Quaternary)
- Conglomerate and sandstone (Pliocene to Quaternary)
- Silicic domes, lava flows and pyroclastic flows (Late Pliocene to early Pleistocene)
- Basaltic and andesitic lava flows (Late Miocene to Pliocene)
- Andesite and basaltic lava flows (Oligocene to middle Miocene)
- Silicic ignimbrites and volcano-sedimentary deposits (Late Cretaceous)
- Intrusive rocks (Late Cretaceous)


Ameca
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San
Antonio
La Vega
Lake
Castro
Urdiales
N
La
Vega
irrigation channel
Buenavista
Ameca River
Ameca River
Aluvial Plain
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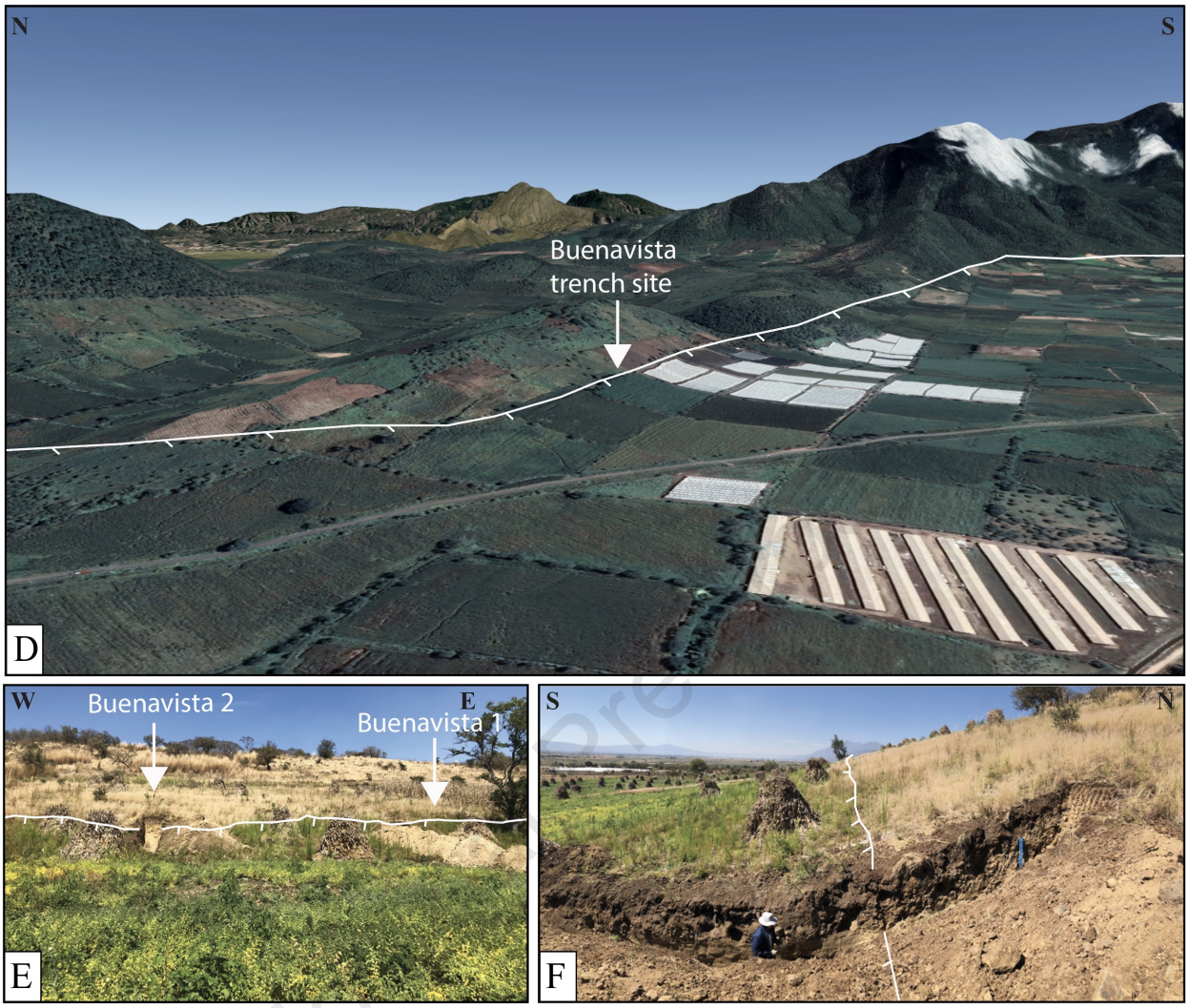
A
2 km
C
B
200 m
Buenavista 2
Buenavista 1
C
50 m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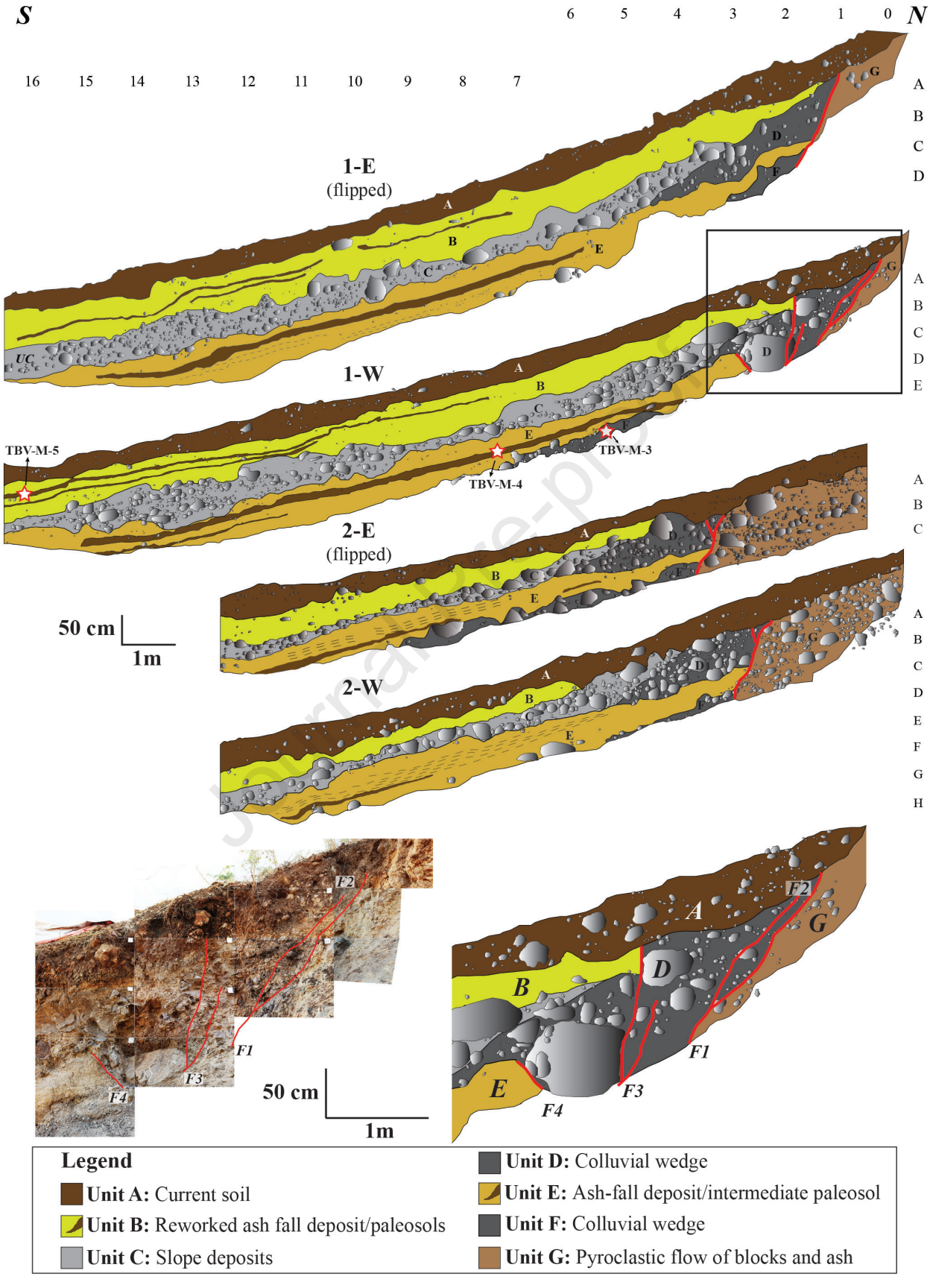
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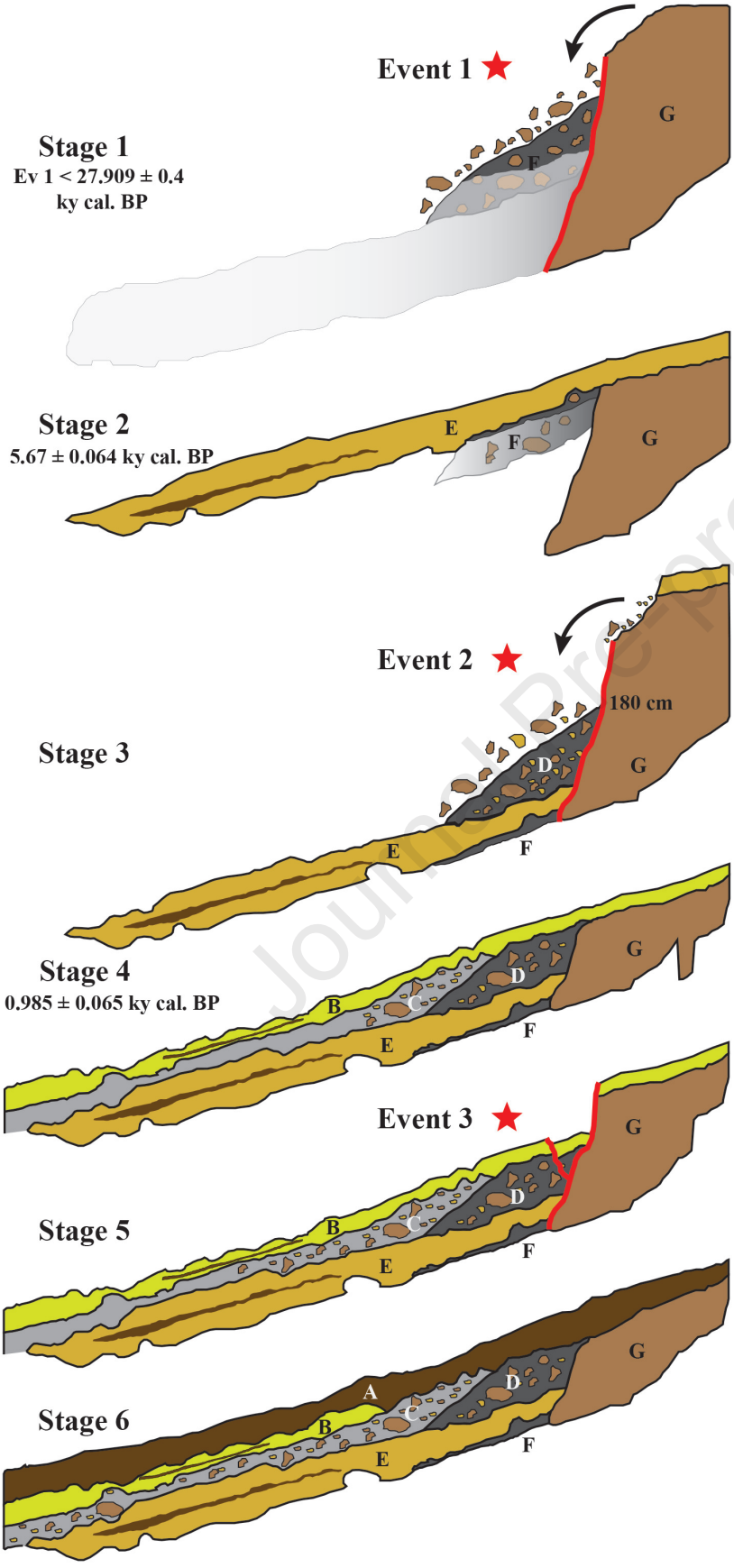
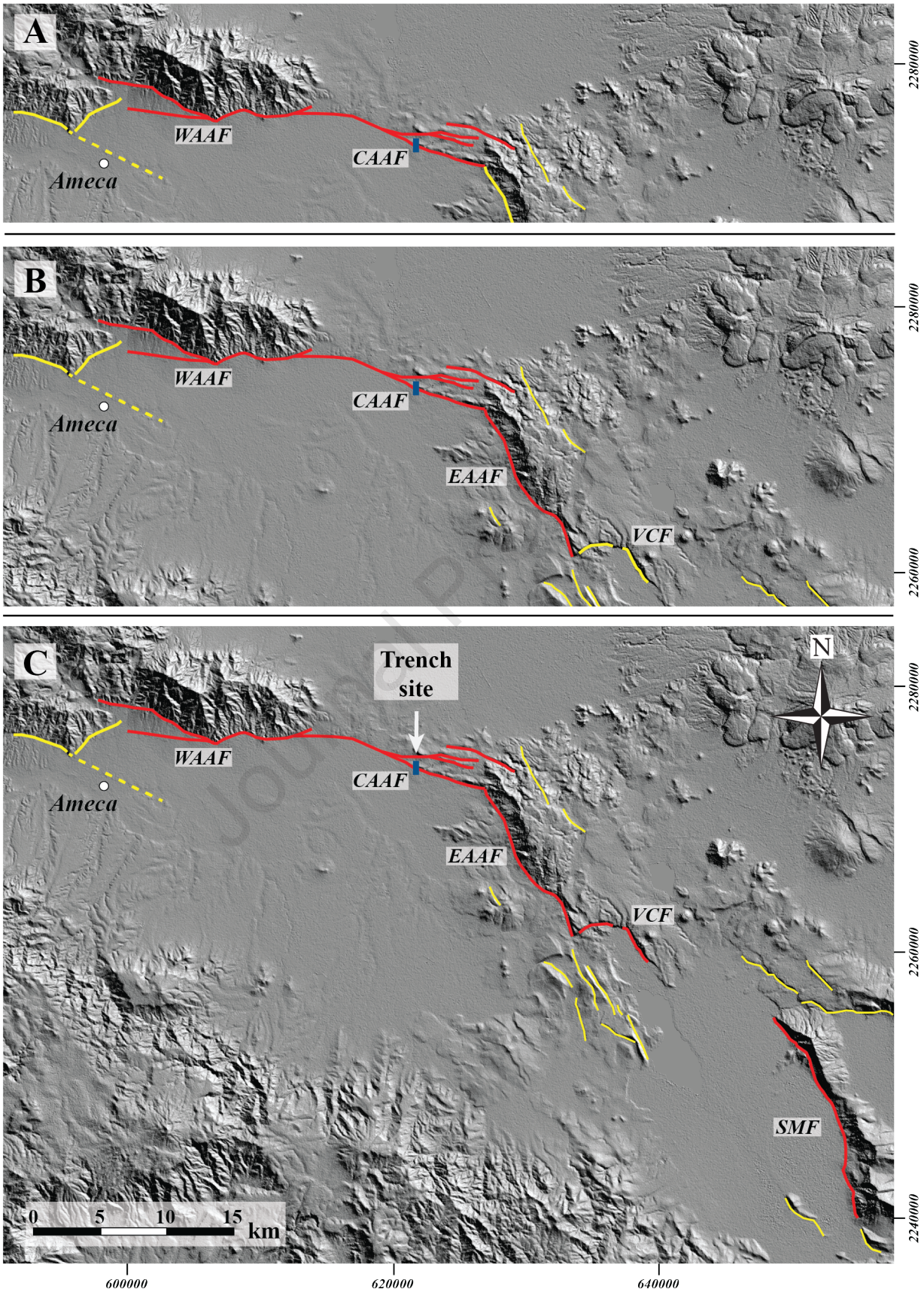
TBV-M-5
TBV-M-4
TBV-M-3
50 cm
1m
F1
F2
F3
F4
Legend
Unit A: Current soil
Unit B: Reworked ash fall deposit/paleosols
Unit C: Slope deposits
Unit D: Colluvial wedge
Unit E: Ash-fall deposit/intermediate paleosol
Unit F: Colluvial wedge
Unit G: Pyroclastic flow of blocks and ash




A
WAAF
CAAF
Ameca
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Ameca
EAAF
VCF
2280000
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CAAF
Ameca
EAAF
VCF
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2240000
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Highlights:

- Largest active fault system described and characterized near Guadalajara, Jalisco.
- First geological evidence of sixteenth century Ameca earthquake
- Undocumented prehistorical earthquakes identified for the first time along the Ameca-Ahuisculco fault.
- Paleoseismology completes the catalog of historical seismicity and contributes to a better evaluation of the seismic hazard.

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To the Guest Editor, Dr. Carlos Costa

Queretaro, December 16, 2020

Special Issue: "VSI:Hazardous Faults"

Dear Dr. Costa,

Manuscript: "First paleoseismological studies in the epicentral area of the sixteenth century Ameca earthquake, Jalisco – México." by Andrés Núñez Meneses, Pierre Lacan, Ramón Zúñiga, Laurence Audin, María Ortuño, José Rosas Elguera, Rodrigo Leon-Loya, Víctor Márquez.

The roles of the authors were as follows:
Núñez Meneses: master student, this study was the subject of his master's research work, formal analysis, writing.
Lacan: Project leader, conceptualization, supervision (thesis director of Andres), leader of fieldwork, data processing, resources, writing.
Zuniga: field assistant, manuscript review and comments, resources.
Audin: Dating of samples, data processing, manuscript review and comments.
Ortuño: Data processing, manuscript review and comments.
Rosas Elguera: field assistant, manuscript review and comments.
Leon-Loya: field assistant, manuscript review and comments
Márquez: field assistant

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Sincerely yours,

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Declaration of interests

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

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