On the search for the source of the 1865-66 Nicaraguan earthquakes:
paleoseismic data from the Cofradía fault, Managua

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Several catastrophic earthquakes struck Managua during the last few centuries. Among the seismogenic fault systems causing them, only two of them have been previously studied through a paleoseismological approach. In this paper, we present new data supporting that the Cofradia fault is a seismogenic fault and the most probable source of the 1865-1866 Nicaraguan earthquakes (Intensity = X). The data were collected at three paleoseismological sites, two of them located on the main trace; La Vaqueria (central-northern part) and El Cocal (central part); and the other one, Piedra Menuda, on an antithetic strand of the southern fault segment. Coseismic evidence consists of liquefaction features, offset layers and colluvial wedges dated with radiocarbon ages and relative cultural ages attributed to pottery fragments. The minimum event displacement observed at the central site, 1 m, and the total length of the mapped geomorphological trace, 39 km, are consistent with maximum expected magnitudes around 7. A minimum slip rate between 1.1 – 1.3 mm/yr is obtained from the new data, reinforcing the previous estimates. The paleoseismic chronology points towards the occurrence of at least three seismic events since 1650 yr BP, the last one occurring after 1281 cal yr BP and shortly before present. Accordingly, the damaging earthquakes of 1865-1866 causing surface alterations in the Tipitapa river could have been produced by the last paleoseismic event on the Cofradia fault. This match leads to an estimated recurrence period between 624 yr and 783 yr for the maximum expected events on this fault.
Online Material: High-resolution photomosaics of trench exposures (Figures S1, S2, and S3)

Introduction

Shallow earthquakes affect repeatedly Managua Metropolitan area, Nicaragua, which lodges more than 2,000,000 people. Managua is built on a graben, whose faults are responsible for the local seismicity. Two destructive earthquakes, which ruptured the surface, occurred within the graben during the 20th century: On March 31, 1931 an earthquake of magnitude mb5.6 (Leeds, 1974) destroyed the city of Managua with about 1,000 fatalities of a population of about 40,000 (Durham, 1931; Sultan, 1931), and on December 23, 1972 a Ms 6.2 earthquake again destroyed the city (ca. 500,000 inhabitants) killing about 11,000 people and injuring more than 20,000 (Brown et al., 1973). In the 19th century, from December 1865 to February 1866, strong earthquakes struck western Nicaragua affecting León, Managua and Granada. It was reported that the Tipitapa River, which drains the Managua Lake into the Nicaragua Lake to the East (Fig. 1), “suffered remarkable topographic changes” during these earthquakes (Montessus de Ballore, 1888).

On the basis of Montessus description, taken from Grases(1974), Peraldo and Montero (1999) located the epicentral area of these earthquakes on the Cofradía fault, which bounds the Managua graben to the East and crosses the Tipitapa River at Tipitapa. The Cofradia fault is 39 km long and therefore capable of generate hazardous earthquakes affecting Managua.

Accepting the hypothesis of Peraldo and Montero, we carried out paleoseismological research on the Cofradia fault with the aim to obtain seismological parameters (Length, slip rate, recurrence) of this fault, as a contribution to the understanding of the seismological hazard of Managua Metropolitan area.
The Managua graben and the Cofradía fault

The Central American Volcanic Chain is developed in relation to the subduction of the Cocos plate below the Caribbean plate. Some of its volcanoes are located along the Nicaraguan Depression (back arc basin; De Mets et al., 1994; Alvarado et al., 2011), which extends from El Salvador to Costa Rica and separates the Tertiary igneous rocks of the interior highlands from the marine sedimentary rocks of the Pacific coastal hills (Fig. 1a). It began to form at the Early Neogene (Funk et al., 2009), and it is filled up by a large volume of Quaternary volcanoclastic deposits. Within the Nicaraguan depression, the N-S oriented Managua graben was formed on a relay zone. It has a length of ca. 40 km and a width of approximately 20 km.

Since the 1972 M 6.2 earthquake, a number of different tectonic interpretations of the Managua graben and its relation to the Nicaraguan depression, the volcanic chain and the subduction zone have been published and relate it to transform faulting and bookshelf faulting models (i.e.: Ward et al., 1974; Dewey and Algermissen, 1974; Ferrez-Weinberg, 1992; Frischbutter, 2002; Cowan et al., 2002; La Femina et al., 2002; Girard and van Wyk de Vries, 2005; Funk et al., 2009).

Submeridians normal faults bound the Managua graben, the Nejapa-Miraflores alignment to the west and the Cofradía fault to the east (Fig. 1b). In its interior, NE-SW left lateral strike-slip faults stand out, as the Estadio fault responsible for the 1931 earthquake and the Tiscapa fault and the related faults which caused the 1972 earthquake (Brown et al., 1973; Ward et al., 1974).

Paleoseismological data from the Aeropuerto fault (Figs. 1b and 1c) in the vicinity of Managua has been published by Cowan et al., (2002). This fault is parallel and
antithetic to the Cofradía fault, and both faults bound the deeper, eastern portion of the
Managua graben (Martínez and Noguera, 1992). The most recent large earthquake on the
Aeropuerto fault occurred during the interval 300-140 yr BP (Cowan et al., 2002). It could
correspond to one of the three largest earthquakes reported in the Managua/Granada
region during this time interval. These are the earthquakes of 1663, 1764, and 1772
(Leeds, 1974), coinciding with volcanic unrest and eruptions from volcanoes in the
region. An earlier earthquake on this fault occurred prior to 560 yr BP and possibly around
2000 yr BP. Cowan et al. (2002) have estimated a vertical slip rate of 0.3 to 0.9 mm/yr
along the Aeropuerto fault.

The Cofradía fault trends N-NNE, dips steeply to the west and runs from the
Masaya volcano, to the North limiting the graben to the east (Fig. 1b and c). The fault
consists of a number en echelon segments that show W-facing scarps reaching heights up
to 15 m and minor antithetic scarps (Fig. 1c). These segments offset several drainage
networks that evidence young fault activity with mainly dip slip, but also some left lateral
motion. Dames and Moore-Lansa (1978) have demonstrated by means of
trenching through some of these scarps in the vicinity of the Tipitapa River (Fig. 1c) that
scarp correspond to the relief created by Holocene activity of different strands of the
Cofradía fault. They have also documented 5000 ± 1000 yr old lake deposits about six
meters above the modern lake shoreline. On this basis, Cowan et al. (2000) have suggested
a slip rate of 1.2 mm/yr for the Cofradía fault.

Method

The approach used was a standard paleoseismological study, involving: 1) A
geomorphological survey by means of 1:33,000 scale aerial photographs of the Cofradía
fault and surroundings. 2) A field survey along the fault to study in more detail some
sectors to select the most suitable sites for trenching. 3) Topographic leveling of
topographical profiles and maps (0.5 m contour levels) of the selected sites. 4) Digging
four trenches, logging its walls and collecting samples for dating. 5) Interpreting the
obtained data in terms of paleoseismic events and parameters.

To constrain the age of paleoseismic events, a number of samples of different
materials were collected from different stratigraphical units: coals and woods, a deer leg
bone fragment, lacustrine bivalve mollusc shells, bulk soil samples and pottery fragments.
Ages derived from $^{14}$C dating of bivalve mollusc shells and charcoal fragments were
obtained at the Accelerator Mass Spectrometry NOSAMS laboratory
(Universitat Autònoma de Barcelona). All $^{14}$C laboratory ages were calibrated and given
as 2σ interval (95% of confidence) and adjusted to the nearest decade, according to the
Calib7.1 software (Stuiver and Reimer, 1993) and the INTCAL13 curves (Reimer et al.,
2013). Pottery fragments have been examined and attributed to particular prehispanic
cultures by E. Espinosa (Director of the Museo Nacional de Nicaragua). The proposed
time spans for the different cultures are those used by GarcíaVásquez (1996). All ages
are in yr BP or cal yr BP ($^{14}$C dates) for better correlation.

**Trenching on the Cofradia fault**

Looking for recent seismic events, we dug trenches in three sites on the southern
part of the Cofradía fault, named, from N to S, La Vaquería, El Cocal y La
Piedra Menuda (**Fig. 1c**). The El Cocal trench yielded most of the relevant paleoseismic
data, part of which has been presented in Ruano et al. (2008).
El Cocal trench site

The Cofradía fault scarp is characterized by linear segments between Masaya volcano and Managua Lake. It becomes sinuous at the El Cocal site, at the shore of the Managua Lake, where it is eroded and slightly retreated and the fault trace is covered by lacustrine terrace deposits. We excavated a 28 m long and 2.5 m deep trench, perpendicular to the general trend of the fault scarp, in front of the eroded scarp (Fig. 1c).

The fault was located 17 m to the west of the present geomorphological scarp.

Two stratigraphic groups deposited under different sedimentary environments can be identified (Fig. 2a, supplementary Figure S1). From base to top, Group 1 presents 2.2 m minimum thickness and it is made of three units of lacustrine sediments (w-y). Within them, a sandy layer (x) can be used as a guide level inside this group. Liquefaction structures affect layer x and layers just beneath it. At the toe of the morphological scarp, the described units are overlain by a wedge of conglomerate with clayish matrix and alternating levels of sands and pebbles of possible fluvial origin (z).

Group 2 (units e-a) unconformably lies on top of the first group. Unit (e) with triangular shape consists of a clast-supported breccia presenting non-stratified structure, coarse sand to gravel matrix and heterometric clasts from the w-y sequence, which reach up to 50 cm in diameter. On top of it, two units are found: unit (d) consists of green clay, rich in sand with disperse sharp pumice clasts overlain by a micro-conglomerate (unit c) showing an erosive base and liquefaction structures, with abundant coal pieces.

Unconformably over the units of both groups, top unit (a) is a massive matrix-supported conglomerate containing 2-10 cm clasts of pumice embedded in volcanic ash
and compacted clay that turn into a sandy matrix breccia eastwards (unit b). The present
day soil (unit s) cap the aforementioned units.

In the eastern part of the trench, the units of the Group 1 are horizontal and become
inclined towards the W in the central part, describing a flexure. The flexure zone is
affected by a set of high angle normal faults, which probably correspond to an upwards
splay of the deeper main Cofradia fault. The units of Group 2 unconformably lay on the
described flexure, and are partially affected by these normal faults.

La Vaquería trench site

Two trenches 17 m long were dug on a 3 m high westward facing scarp partially
covered by alluvial fan deposits ([Fig. 1c, Fig. 2b, supplementary Figure S2]). The up-
thrown block consists of volcanic air-fall deposits (units 1 to 4), and the downthrown
block consists of alluvial fan units (units 5 to 10). The fault with a minimum accumulated
displacement of 2.5 m separating both blocks affects the lower levels identified of the fan
(5 to 7) and is sealed by the uppermost ones (9-10).

La Piedra Menuda trench site

An antithetic scarp to the Cofradía fault was investigated at two 15 and 17 m long
trenches perpendicular to the fault with the aim of detecting ruptures affecting the
historical Masaya lava flows (280 and 178 yr BP, [Fig. 1c, supplementary Figure S3]).
These flows are presumably covered in that site by a very recent small alluvial fan, which
onlaps a scarp developed on older Holocene deposits. Neither the main fault nor the lava
flow was reached by trenching. Only the southernmost of the two trenches showed faults
affecting a volcanic deposits and a related colluvial deposit ([Fig. 2c]). We could not date
the colluvial deposits, although they appear to be relatively recent according to its low
degree of pedogenesis. The volcanic deposit forms a scarp affected by toppling and is made up of a sequence of volcanic tuff attributed to the Masaya group, probably deposited during the Holocene (Fig. 2c). The other trench showed the very recent alluvial fan apparently overlying the fault and containing plastic bottles, baby clothes, plastic bags, etc. It lies on an undisrupted clastic unit that yielded a piece of charcoal dated 1333+-45 yr BP. This age is older than the missing in the trench site lava flows, probably owing to its irregular contour. So, this fault strand seems to have been quiet since 1333+-45 yr BP.

Paleoseismological evidences The interpretation of the results obtained from the El Cocal and La Vaquería trenches evidences recent seismic activity of the Cofradía fault. The Piedra Menuda trenches are not considering in this section due to high rate of sedimentation that avoid reaching paleoseismic evidences by trenching.

El Cocal area

In El Cocal trench, among twenty two samples were taken but only five of them yielded $^{14}$C dating results. Three samples are consisted of characteristic pottery fragments, which allowed constraining the ages of the different units (Table 1, Fig. 2a). Accordingly, the first stratigraphic sequence (units w to y) is Middle Holocene in age, whereas the second sequence (units e to a) consists of historical sediments.

Evidence of the oldest seismic activity is reflected by liquefaction structures (Fig. 2a, columns 0 - 7, northern and southern walls) in beds belonging to Group 1 (units w and x). Since no liquefaction is observed in Group 2, we suspect that this seismic activity should have occurred in the middle of the Holocene, although no individual events can be determined with the available data.
In relation to the deposits of the Group 2, four paleoseismic events were deduced, three of them relatively well constrained on time. From younger to older these events are (Fig. 2a and Fig. 3):

- **Event 4.** Fault F2 displaces the base of unit a by a maximum of 0.3 m. The fault vanishes progressively upwards inside the massive unit a. The topographical surface does not show any scarp at the prolongation of this fault. However, we consider that this displacement could have affected the upper part of this unit. Reworking of the upper part of unit a during strong storms cannot be discarded, as it occurred during the floods related to Hurricane Mitch in 1998. In addition, the upper part of unit a is strongly bioturbated. This could explain the upwards vanishing of the fault. This event occurred between 1281 cal yr BP and short before present.

- **Event 3.** Fault F1 cuts the base of unit e, but does not displace the base of unit a, which lies on an erosional surface. During event 3 the vertical displacement on fault F2 after restoration of event 4 is 0.3 m similar to a minimum of 0.30 m is observed on fault F1 (the base of e does not crop out in the downthrown wall). Since unit e was completely eroded east of F2 before deposition of a, the contribution of faults located east of F2 to the total displacement of this event is unknown. The minimum vertical displacement for this event is 0.6 m. Notice that the absence of units d and e ast of columns 19-20 does not allow us to observe the relationship of faults F1 and F2 with these units. Event 3 occurred after deposition of e and before the deposition of a, i.e., in the time span between 1650 and 600 yr BP.

- **Event 2.** The wedge-shaped breccia, unit e, is interpreted as a colluvial wedge resulting from activity on fault F2. Prior to deposition of unit a, unit e was totally eroded east of F2. The maximum observable thickness of unit e is 0.8 m (southern wall, west of F1). Taking into account that part of this unit was eroded, its original thickness was surely
larger. As a consequence the displacement along the fault responsible for event 2 was likely greater than 1 m. F2 is more likely to have caused the colluvial wedge and not the faults located to the east (F3 and F4). These faults have too small associated displacements as to generate such a thick wedge (e). This event occurred shortly before the deposition of unit e, constrained by 1650 yr BP (maximum age of e) and 1150 cal yr BP (minimum age of e assuming it is older to unit c, which is dated as 1411 ± 109 cal yr BP).

**Event 1.** Several features evidence an older event: 1) Faults displacing the base of unit x, but not affecting the base of e, which lies on an erosional surface. 2) The different thicknesses (or presence/absence) of unit x on both sides of the fault zone suggest differential erosion related to uplift on the eastern wall following deposition of x. This erosion hid the behavior of faults east on F2 during this event. This event is badly constrained by maximum age of unit w (7831 cal yr BP) and the minimum age of unit e (given by age of unit c, 1150 cal yr BP).

*La Vaquería area*

Units 5 and 7 were interpreted as colluvial wedges owing to their lithology and geometry. This data suggests at least a minimum of two seismic events prior to the deposition of unit 9: event 3 is evidenced by the fault cutting colluvial wedge 7, and event 2, by the deposition of this colluvial wedge. The flexure of Unit 9 (south wall) could be relate with the latest event. An older event (event 1) is probable, if the interpretation of unit 5 as a colluvial wedge is correct. Unfortunately, only a piece of charcoal taken from the lower part of unit 5 was available for dating at this site (7062±254 cal yr BP), suggesting an approximate age for the oldest event. The two younger events postdate it, but their age could not be constrained, although the flexure of unit 9.
Discussion

We focussed the discussion on the data corresponding to the last three events observed in El Cocal trench, which are better constrained in age. At this site the fault zone is located at the lake shore, where sedimentation and erosive processes alternate. In spite of this, the last three events, which occurred in historical times, are relatively well recorded.

Slip rate. The total minimum vertical displacement observed for the last three events is 1.9 m (event 2: 1 m, event 3: 0.28 + 0.30 m; event 4: 0.32 m). So, for the last 1714 - 1398 yr BP, i.e., since the occurrence of the second event, the minimum vertical slip is 1.1 – 1.3mm/year. This is a minimum value since displacements along faults east of fault F2, tilting of beds, and the eroded part of unit e were not considered. Therefore, this short term vertical slip rate value matches well with the 1.2 mm/year mid-term slip rate suggested by Cowan et al. (2000) for the area, and is larger than the 0.3-0.9 mm/a slip rate estimated by Cowan et al. (2002) for the seismogenic Aeropuerto fault.

To corroborate the four deduced paleoseismic events along the geological section in El Cocal trench, a vertical slip rate of 1.1 mm/year was considered, based on observed deformation, to perform a retrodeformation analysis, using layer x as a reference marker in the surface flexure (Fig. 4). This flexure seems controlled by the splay of faults developed at the upwards termination of the Cofradía fault. We did not take into account faults east of F2 in the restoration since, to draw a plausible section, their offsets need to be small and thus, negligible. Moreover, the amount of these offsets is unknown because of erosion prior to deposition of unit a. Restoration of events 2 to 4 along faults F1 and F2 shows a total recovery of F1 and an important recovery of F2. A total recovery of F2 could be probably obtained if the total thickness of the wedge e were taken into account
instead of only the preserved part. The possible tilting of the beds during these events was not considered. The remaining offset of bed x west of F1 has to be attributed to the activity of faults located west of F1 and to events occurring between ca. 7000 and 1650–1150 cal yr BP.

We calculated the maximum magnitude expected from our results. The minimum vertical displacement of the surface for the maximum event observed is ca1 m (event 2). This value correspond to a minimum magnitude of Mw = 6.78, and a minimum fault length of 24 km according to empirical relationships for normal faults (Wells and Coopersmith, 1994). Such a length is under the total length mapped for the Cofradia fault trace (39 km). Since the observed displacements are minimum values in this site, and other scarps eastwards have been described across the same section (Dames and Moore-Lamsa, 1978), it is reasonable to accept that the entire Cofradia fault is capable of rupture in a single event. Updated relationships proposed by Villamor et al. (2001) are recommended by Stirling et al. (2013) for normal faults in volcanic environments with crustal thickness greater than 10 km, as is the case of the Nicaraguan depression (e.g., Cáceres, 2003; Mackenzie et al., 2008), suggest a maximum Mw of 7 (β = 0.34) for a 39 km long surface fault trace.

Recurrence. The last three events (E2, E3, E4) have occurred since the time of event 2 (E2), i.e., since 1650 yr BP as the older and 1150 cal yr BP as the younger possible date. If we considered that the 1865 earthquake was generated by the Cofradia fault and it is our event 4 at el Cocal, a time span of 1249–1565 yr will cover the three events, corresponding to two seismic cycles of minimum 624.5 yr and maximum 782.5 yr. Assuming the last event was that of 1865, any of these seismic cycle boundaries
matches with the event chronology obtained here for the last 3 events (Fig. 3), which point out that the fault could have a characteristic behavior.

Last event. Only the oldest possible age of the last event was constrained. This event (event 4 at El Cocal) occurred between 1281 cal yr BP and short Before Present. The catalog of Nicaraguan earthquakes compiled by Leeds (1974) begins on 1520 (sixteen century) and that of Central America done by Peraldo and Montero (1999) on 1530. Leeds’ catalog includes a larger number of earthquakes than Peraldo and Montero’s catalog, but this latter one offers more detailed information on some particular earthquakes. Leeds classifies the earthquakes in five classes, from A (the largest earthquakes) to E (the smallest ones), and assigns an arbitrary body-wave magnitude to all events for which no magnitude has been previously published. The largest earthquakes affecting western Nicaragua are B-class earthquakes: three during XVII century (1609, 1648 and 1663), the earthquake of May 1844 and that of February 1866 (Leeds, 1974). It is likely that the last event described here could correspond to one of the aforementioned earthquakes. The descriptions of surface alterations along the Tipitapa River during the earthquakes of 1865-1866 described in Montessus de Ballore (1888) lead us to propose the Cofradia fault as the most probable source of this earthquake. The time range for event 4 at the El Cocal site is compatible with that date. Additionally, the Cofradia fault is the closest fault to the Tipitapa River (Fig. 1b and c) with known geomorphic expression.

Conclusion

The paleoseismological data compiled in this work provide new insight into the seismogenic behavior and earthquake history of the Cofradia fault. The maximum rupture length is 39 km and its minimum vertical slip rate is 1.1 – 1.3 mm/year. The maximum
earthquake magnitude of the fault is likely to be around 6.9 ± 0.1, with a mean recurrence
interval between 624.5 and 782.5 yr.

Among the three paleoseismic sites studied, El Cocal (central part of the trace) supplied the most complete record of seismic events. At both La Vaquería (north-central part of the trace) and El Cocal site, middle Holocene events were identified, one of them probably occurring before 7062 ± 254 cal yr BP. The younger events recorded at El Cocal are named event 2, occurring between 1650 yr BP and 1150 cal yr BP; event 3, taking place between 1650 and 600 yr BP; and event 4, which probably took place a short time before the Present and after 1281 cal yr BP. Any of those events could match with the two younger events recorded at La Vaquería, which suggest common surface ruptures of these parts of the fault.

Accordingly, the Cofradia fault is a probable source of the Nicaraguan earthquakes (1865 – 66, M = 7-7.7, Peraldo and Montero (1999)), which may coincide with the last paleoseismic event (E4). This is the most conspicuous fault with geomorphological expression crossed by the Tipitapa River, which suffered surface alterations during those historical events. Moreover, the surface trace of the Cofradia fault (39 km), in case of a complete rupture, can have a maximum moment magnitude Mw = 7, which is consistent with the 1865-66 events estimated earthquake magnitudes.

Data and Resources

All data used in this paper come from published sources listed in the references.

Acknowledgments

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Trenching campaign was conducted during the dry season of 2007 with the help of Oriol Piqué and the financial support of Spanish projects CGL 2006-27 072 E/BTE and AECI C/6111/06.

References


**Figures and Tables**

**Figure 1.** Geodynamical and geological setting. a) Middle America Volcanic Chain in plate tectonic framework. b) Managua graben in the Nicaraguan Depression. Location in Fig 1a. AF, Airport Fault; CF, Cofradia Fault; EF, Estadio Fault; MF, Mateare Fault; NMF, Nejapa-Maraflroes alignment; TF, Tiscapa Fault. c) Deeper eastern Managua graben area showing the southern sector of Cofradia Fault and trench locations.

**Figure 2.** Logs of the El Cocal (a) and La Vaqueria (b) trenches showing the location of main faults and dating samples. A photolog of PiedraMenuda trench (c) is included. The main fault is suggested by the white arrows.

**Figure 3.**Paleoearthquake chronology of the studied sites. In the upper part of the graph, the dating results for the el Cocal trench are plotted. In the lower part, the event time constraints for the El Cocal and La Vaqueria are determined by the age of the corresponding bracketing units.

**Figure 4.** Retrodeformation scheme for the El Cocal trench North wall. a) Schematic cross section of Present day geometry after event 4, including a reconstruction of the eroded and buried continuation of marker layer x. The depth of layer x in the down-thrown wall was calculated by considering an approximate age of 5,000 BP for it and a 1.1 mm/year vertical slip rate for the Cofradia fault. b) Geometry of layers after event 3. c) Geometry of layers after event 2, showing a total recovery of fault 1. d) Geometry of layers
previous to event 2 still shows a slight flexure of x, probably associated to faulting along other secondary faults of the splay and along the main faults at depth.

Table 1. Dating results for the samples taken at El Cocal, La Vaqueria and La Piedra Menuda trenches.

Online Supplementary Material

Figure S1. Photomosaic of the El Cocal trench, N and S walls.

Figure S2. Photomosaic of the La Vaqueria trench, N and S walls.

Figure S3. Photomosaic of the Piedra Menuda trench, S wall.
<table>
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<th>Trench (Unit)</th>
<th>Sample</th>
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<th>Calibrated age ** or archeological age (yrs)</th>
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<td>630 ± 22 AD</td>
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</table>

* Conventional radiocarbon ages reported by NOSAMS. Calculations assume a Libby half-life (5568 yr). Uncertainties are 1 Standard deviation counting errors.

** Dendrochronologically calibrated, calendar age ranges from CALIB 5.1 software (Stuiver and Reimer, 1993), 2 standard deviation uncertainty and the INTCAL04.14c curves (Reimer et al, 2004)
Fig. 1 Geodynamical and geological setting. a) Middle America Volcanic Chain in plate tectonic framework. b) Managua graben in the Nicaraguan Depression. Location in Fig 1a. AF, Airport Fault; CF, Cofradía Fault; EF, Estadio Fault; MF, Mateare Fault; NMF, Nejapa-Maratíores alignment; TF, Tiscapa Fault. c) Deeper eastern Managua graben area showing the southern sector of Cofradía Fault and trench locations.
Figure 2. Logs of the El Cocal (a) and La Vaqueria (b) trenches showing the location of main faults and dating samples. A photolog of Piedra Menuda trench (c) is included. The main fault in Piedra Menuda is suggested by the arrows on top of the photograph.
Figure 3. Paleoearthquake chronology of the studied sites. In the upper part of the graph, the dating results for the El Cocal trench are plotted. In the lower part, the event time constraints for the El Cocal and La Vaqueria are determined by the age of the corresponding bracketing units.
Figure 4. Retrodeformation scheme for the El Cocal trench North wall. 
a) Schematic cross section of Present day geometry after event 4, including a reconstruction of the eroded and buried continuation of marker layer x. The depth of layer x in the down-thrown wall was calculated by considering an approximate age of 5,000 BP for it and a 1.1 mm/year vertical slip rate for the Cofradia fault. 
b) Geometry of layers after event 3. c) Geometry of layers after event 2, showing a total recovery of fault 1. d) Geometry of layers previous to event 2 still shows a slight flexure of x, probably associated to faulting along other secondary faults of the splay and along the main faults at depth.
Electronic Supplement

**Manuscript title:** On the search for the source of the 1865-66 Nicaraguan earthquakes: paleoseismic data from the Cofradía fault, Managua graben (Nicaragua)

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This electronic supplement contains high resolution photomosaics of the walls of the studied trenches.

**Figure S1.** Photomosaic of the El Cocal trench, N and S walls.

**Figure S2.** Photomosaic of the La Vaqueria trench, N and S walls.

**Figure S3.** Photomosaic of the El Cocal trench, S wall.