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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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) andEl Cocal(central part); and the other one, PiedraMenuda, 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, reinforcingtheprevious 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 BPand shortly Before Present.Accordingly, the damaging earthquakes of 1865-1866 causing surface alterations in the Tipitapariver 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 yrfor 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 localseismicity. 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 M_s 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 struckwestern 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 ofgenerate 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 developedin 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 EarlyNeogene(Funk *et al*., 2009), and it is filled up by a large volume of Quaternary volcanoclasticdeposits. Within the Nicaraguan depression, the N-S oriented Managua graben wasformed 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 totransform faultingand bookshelf faulting models(i.e.: Ward *et al*., 1974; Dewey and Algermissen, 1974; Ferrez-Weinberg, 1992; Frischbutter, 2002; Cowan *et al*., 2002; La Feminaet *al*., 2002; Girard and van Wyk de Vries, 2005;Funk *et al*., 2009).

Submeridiannormal faultsbpund 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 interval300-140yr 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 BPand 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 Cofradia fault trends N-NNE, dips steeply to the west and runs from the Masaya volcano, to the Northlimiting 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 trenchingthrough some of these scarps in the vicinity of the Tipitapa River (**Fig. 1c**) that scarps correspond to the relief createdbyHolocene activity of different strands of the Cofradía fault. They have also documented 5000±1000yr 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 Cofradia 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) Totopographic 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 (UniversitatAutònoma 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 MuseoNacional 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.

Trenchingon 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 PiedraMenuda(**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 scarpis characterized by linear segments between Masaya volcano and Managua Lake. Itbecomes 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 excavateda 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 thewest 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 2.2m minimum thickness and it is made of three units of lacustrine sediments (*w*-*y*).Within them, asandy 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 ofconglomerate 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 on a clast-supported breccia presenting non-stratified structure, coarse sand to gravel matrix and heterometricclasts from the w-y sequence, which reachup to 50cm in diameter.On top of it, two units are found: unit (*d*) consists of green clay, rich in sand with disperse sharp pumice clastsoverlain by a micro-conglomerate (unit *c*) showing an erosive base and liquefaction structures, with abundant coal pieces.

Unconformablyover the units of both groups, top unit (*a*) is a massivematrix-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*)capsthe aforementioned units.

In the eastern part of the trench, the units of the Group 1are 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 2.5m 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 trenchsite

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 trenchesevidences recent seismic activity of theCofradía fault. The PiedraMenuda trenchers 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 onlyfive of them yielded^{14}C dating results. Three samples areconsisted ofcharacteristicpottery fragments,which allowed constraining the ages of the different units (**Table 1**, **Fig. 2a**). Accordingly, the first stratigraphicsequence (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**, columns0 -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 determinedwith 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 thebase of unit *a* bya 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 stormscannot 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 between1281 calyr BP and short before present.

- **Event 3**. Fault F1cuts the base of unit*e*, but does not displace the base of unit*a*, which lies onan erosional surface.During event 3 the vertical displacement on fault F2 after restoration of event 4 is 0.3msimilar 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 0.6m. Notice that the absence of units *d* and *c*east 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 1650and 600 yr BP).

- **Event 2**.The wedge shaped breccia, unit *e*, is interpreted asa 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. F2is more likely to have caused the colluvial wedge and not the faults located to the east (F3 and F4). These faults havetoo small associated displacementsas to generatesuch a thick wedge (e).This event occurred shortly before the deposition of unit *e*, constrained by 1650 yr BP (maximum age of *e*) and 1150calyr BP (minimum age of *e* assuming it is older to unit *c*, which is dated as 1411 ± 109calyr 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 differentialerosion related to uplift on the eastern wall following deposition of *x*. This erosion hidedout the behavior of faults east on F2 during this event. This event is bad constrained by maximum age of unit *w* (7831 calyr BP) and the minimum age of unit *e* (given by ageof unit c,1150 calyr 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 calyr 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 matcheswell 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 eventsalong 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 flexureseems 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 ofrupture 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 (б = 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., since1650 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 spam of 1249 – 1565yr will cover the three events, corresponding to two seismic cycles of minimum624.5yr andmaximum 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 outthat the fault could have a characteristic behaviuor.

*Last event.*Only the oldest possible age of the last event was constrained. This event (event 4 at El Cocal) occurred between 1281 calyr BPand 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 TipitapaRiver 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 4at 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 paleosesimological 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 is1.1 – 1.3 mm/year.The maximum earthquake magnitude of the fault is likely to be around 6.9 ± 0.1, witha 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 calyr BP. The younger events recorded at El Cocal are named event 2, occurring between1650 yr BPand1150 cal yr BP; event 3, taking place between 1650and 600 yr BP; and event 4, which probably took place a short time Before the Present and after 1281 calyr BP. Any of those events could match with the two younger events recorded at La Vaqueria, 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 havea maximum moment magnitudMw = 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.

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References

Alvarado, D., C. DeMets, B. Tikoff, D. Hernández, T. F. Wawrzyniec, C. Pullinger, G. Mattioli, H. L. Turner, M. Rodríguez and F. Correa-Mora (2011). Forearc motion and deformation between El Salvador and Nicaragua: GPS, seismic, structural, and paleomagneticobservastions. Lithosphere **3(1)** 3-21.

Brown, Jr., R.D., P.L. Ward and G. Plafker (1973).Geologic and seismologic aspects of the Managua, Nicaragua, earthquakes of December 23, 1972, Geol. Surv. Prof. Pap. **838** 34pp.

Cáceres, D. (2003). Earthquake Sources and Hazard in Northern Central America. Comprehensive Summaries of Uppsala Dissertations, Uppsala University, 28 pp.

Cowan, H., M. N. Machette, X. Amador, K. S. Morgan, R. L. Dart and L. A. Bradley (2000*). Map and Database of Quaternary Faults in the Vicinity of Managua, Nicaragua.*Open-File Report , 00-437.

Cowan, H., D. Pantosti, P. Martini, W.Strauch, and Workshop Participants (2002). Late Holocene Earthquakes on the Aeropuerto Fault, Managua, Nicaragua, Bull. Seism. Soc. Am. **92** 1694-1707.

Dames and Moore-Lamsa (1978). *Informe final del Estudio geológico de las ciudades del sistema metropolitano: Managua, Nicaragua*, Vice Ministerio de Planificación Urbana, Managua, 143 pp.

DeMets, C., R.G. Gordon, D.F. Argus, and S. Stein (1994).Effect of recent revisions to the geomagnetic reversal time scale on estimate of current plate motions, Geophys. Res. Lett. **21** 2191-2194.

Dewey, J.W. and T. Algermissen (1974).Seismicity of the Middle America Arc-trench System near Managua, Nicaragua.Bull.Seism. Soc. Am. **64(4)** 1033-1048.

Durham, H.W. (1931). Managua – Its Construction and Utilities.Engineering News-Record 696-700.

Ferrez Weinberg, R. (1992). Neotectonic development of western Nicaragua.Tectonics**11(5)** 1010-1017.

Frischbutter, A. (2002): Structure of the Managua graben, Nicaragua, from remote sensing images. GeofísicalInternacional**41(2)** 87-102.

Funk, J., P. Mann, K. McIntosh, and J. Stephens (2009). Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median trough, El Salvador, based on seismic-reflection profiling and remote sensing data, Bull. Geol. Soc. Am. **121(11-12)** 1491-1521.

García Vásquez, R. (1996). Hallazgos recientes en Acahualinca (N-Ma-61), in *La segunda temporada del proyecto "Arqueología de la Zona Metropolitana de Managua"* Frederick W. Lange, (Editor , Managua, 99-102.

Girard, G. and B. Van Wyk de Vries (2005). The Managua Graben and Las Sierras-Masaya volcànic complex (Nicaragua); pull-apart localization by an intrusive complex: results from analogue modelin. J. Volcanology and Geothermal Res. **144** 37-57.

Grases, J. (1974). *Sismicidad de la Región Centroamericana asociada a la Cadena volcánica del Cuaternario*. 2. Instituto de Geociencias, Caracas, 253 pp.

La Femina, P., T. H. Dixon, and W. Strauch (2002). Bookshelf faulting in Nicaragua. Geology **30(8)** 751-754.

Leeds, D. J. (1974). Catalog of Nicaraguan earthquakes, Bull. Seis. Soc. Am. 64 1135-1158.

MacKenzie, L., G. A. Abers, K. M. Fischer, E. M. Syracuse, J. M. Protti, V. Gonzalez, and W. Strauch (2008), Crustal structure along the southern Central American volcanic front, Geochem. Geophys. Geosyst., 9, Q08S09, doi:10.1029/2008GC001991.

Martínez, W., and E. Noguera (1992).Geological framework of earthquakes occurrence in Nicaragua, Central America, J.Geol Soc. Japan**98** 165-176.

Montessus de Ballore, F. (1888). *Tremblements de terre et eruptionsvolcaniques en Centre Amériquedepuis la conquêteespagnolejusqu'à nos jours*. Soc. Sci. Nat de Saone et Loire., Dijon, 233 pp.

Peraldo, G., and W. Montero (1999).*Sismología histórica de América Central*, IPGH, México, 347 pp.

Reimer, P. J., E.Bard, A.Bayliss, J. W. Beck, P. G. Blackwell,.C.Bronk Ramsey, C. E. Buck,H. Cheng, R. L. Edwards, M. Friedrich, P. M.Grootes, T. P., Guilderson, H. Haflidason, I. Hajdas, C. Hatté, T. J. Heaton, D. L. Hoffmann, A. G. Hogg, K. A. Hughen, K. F. Kaiser, B. Kromer, S.W. Manning, M. Niu, R. W. Reimer, D. A. Richards, E. M. Scott, J. R., Southton, R. A. Staff, C. S. M. Turney and J. van der Plicht(2013). IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 yearscal BP. Radiocarbon, 55(4), 1869-1887

Ruano, P, C. Rubí, E. Masana, M. Ortuño, O. Piqué, and P. Santanach (2008).Paleosismología en la falla de Cofradía, Managua, Nicaragua: resultados preliminares, Geo-Temas **10** 1059-1062.

Stirling, M., T. Goded, K. Berryman, and N. Litchfield (2013).Selection of Earthquake Scaling Relationships for Seismic-Hazard Analysis. Bull. Seism. Soc. Am. **103(6)** 1–19, doi: 10.1785/0120130052.

Stuiver, M. and P. J. Reimer (1993).*CALIB User's Guide Rev. 3.0.*University of Washington, Quaternary Isotopes Laboratory.

Sultan, D .I. (1931).The Managua earthquake, Military Engr. **23** 354-361.

Villamor, P., R. K. R. Berryman, T. Webb, M. Stirling, P. McGinty, G. Downes, J. Harris, and N. Litchfield (2001). *Waikato Seismic Loads: Revision of Seismic Source Characterisation*, GNS Client Report 2001/59.

Ward. P, J, Gibbs, D. Harlow, and Q. Aburto (1974). Aftershocks of the Managua, Nicaragua, Earthquake and the Tectonic Significance of the Tiscapa Fault, Bull.Seism. Soc. Am. **64(4)** 1017-1029.

Wells, D.L., and K.J.Coppersmith (1994): New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seism. Soc. Am. **84(4)** 974-1002.

Figures and Tables

Figure 1. Geodynamical and geological setting. a) Middle America Volcanic Chain in plate tectonic framework. b) Managua graben in the NicaraguanDepression. Location in Fig 1a. AF, Airport Fault; CF, Cofradía Fault; EF, Estadio Fault; MF, Mateare Fault;NMF, Nejapa-Maraflores 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 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 event2, showing a total recovery of fault 1. d) Geometry of layers

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

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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 PiedraMenuda trench, S wall.

Table 1

Table 1. Dating results

Trench (Unit)	Sample	14C age* (yrs BP)	Calibrated age ** or archeological age (yrs)	Material/consideration
El Cocal (*w*)	MCN-3	6890±40	5794 ± 87 BC	Mollusc
El Cocal (*w*)	MCN-13	5960±30	4853 ± 84 BC	Charcoal
El Cocal (*e*)	MCS-7		300-800 AD	Pottery fragment-trichromed Tola type, attributed to Bagaces cultural period
El Cocal (*c*)	MCS-6	1490±40	579 ± 37 AD	Charcoal/ preferred age for the unit
El Cocal (*c*)	MCN-1		300-800 AD	Pottery fragment attributed to Bagaces cultural period
El Cocal (*a*)	MCS-5	2020±30	24 BC ±82	Charcoal, reworked fragments
El Cocal (*a*)	MCN-5		800-1350 AD	Pottery fragment-striated Sacasa type attributed to Sapoá cultural period
El Cocal (*a*)	MCN-11	1260±30	726 AD ±57	Charcoal
El Cocal (*a*)	MCN-9		800-1350 AD	Pottery fragment-Papagayo type attributed to Sapoá cultural period
La Vaqueria-2 (5)	MVS2-1	6200±95	5136 ± 230 BC	Charcoal
Piedra Menuda	MPN2-4	1420±35	630 ± 22 AD	Charcoal

* 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)

Figure 1

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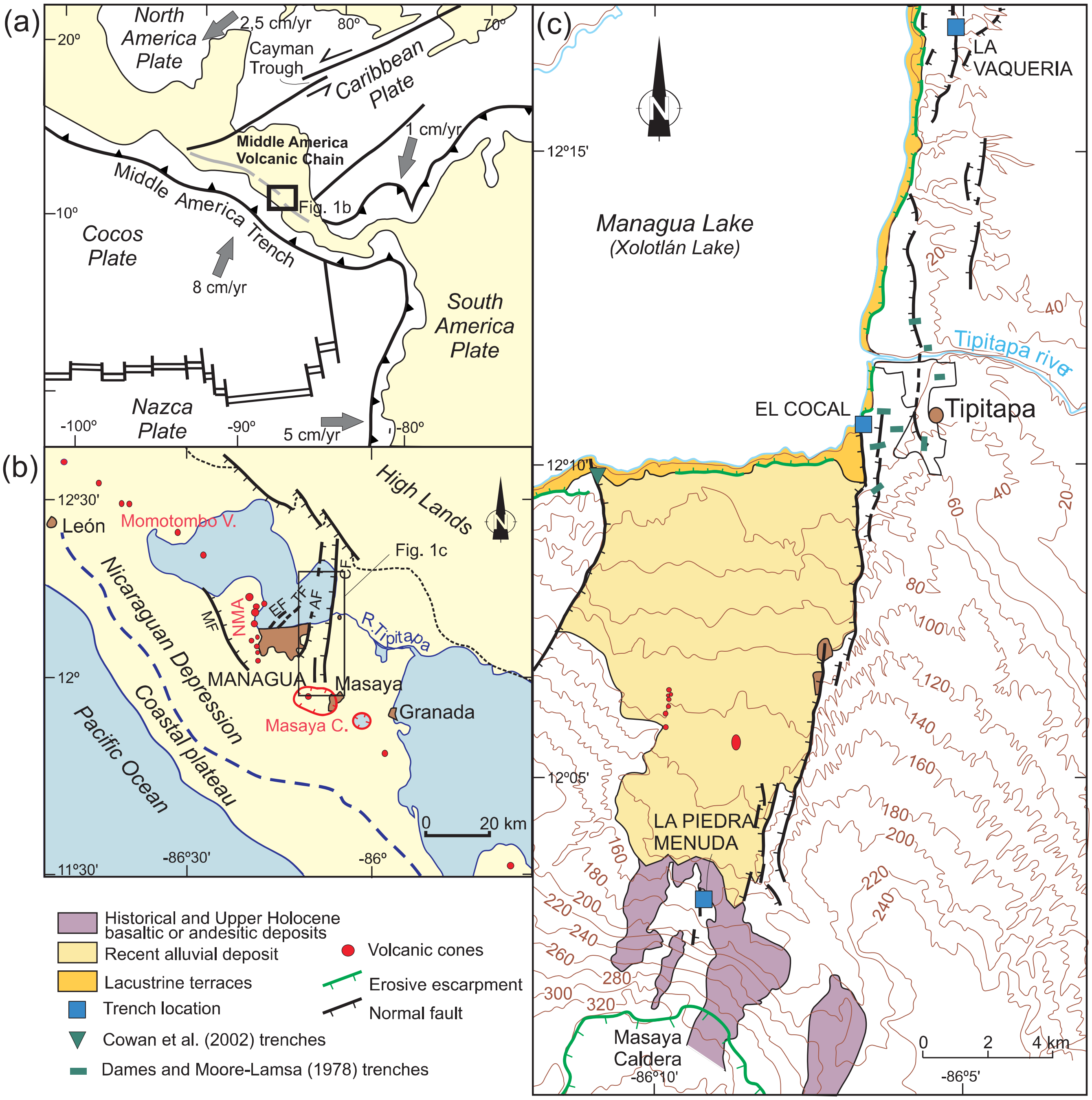

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Figure 2
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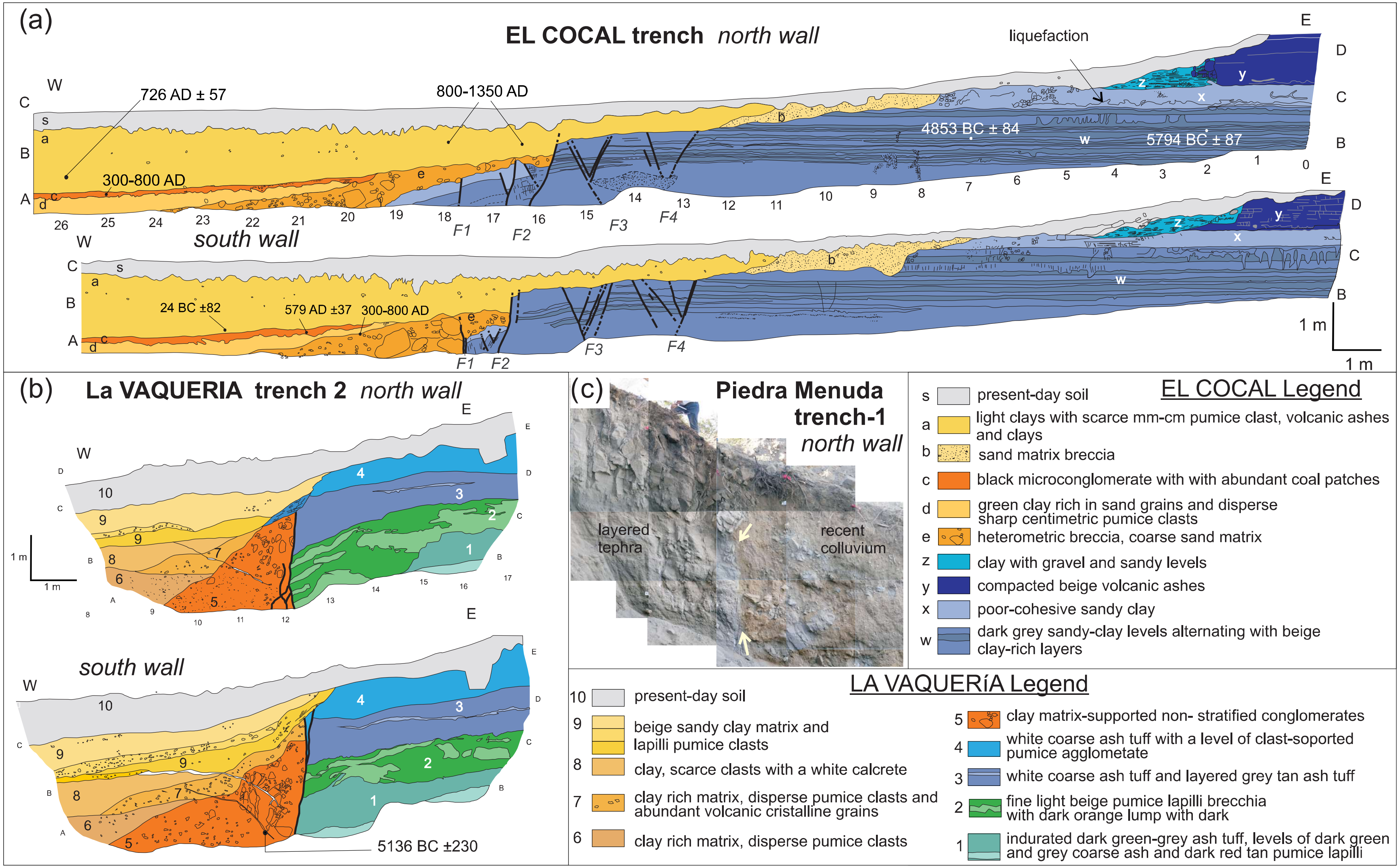

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Figure 3
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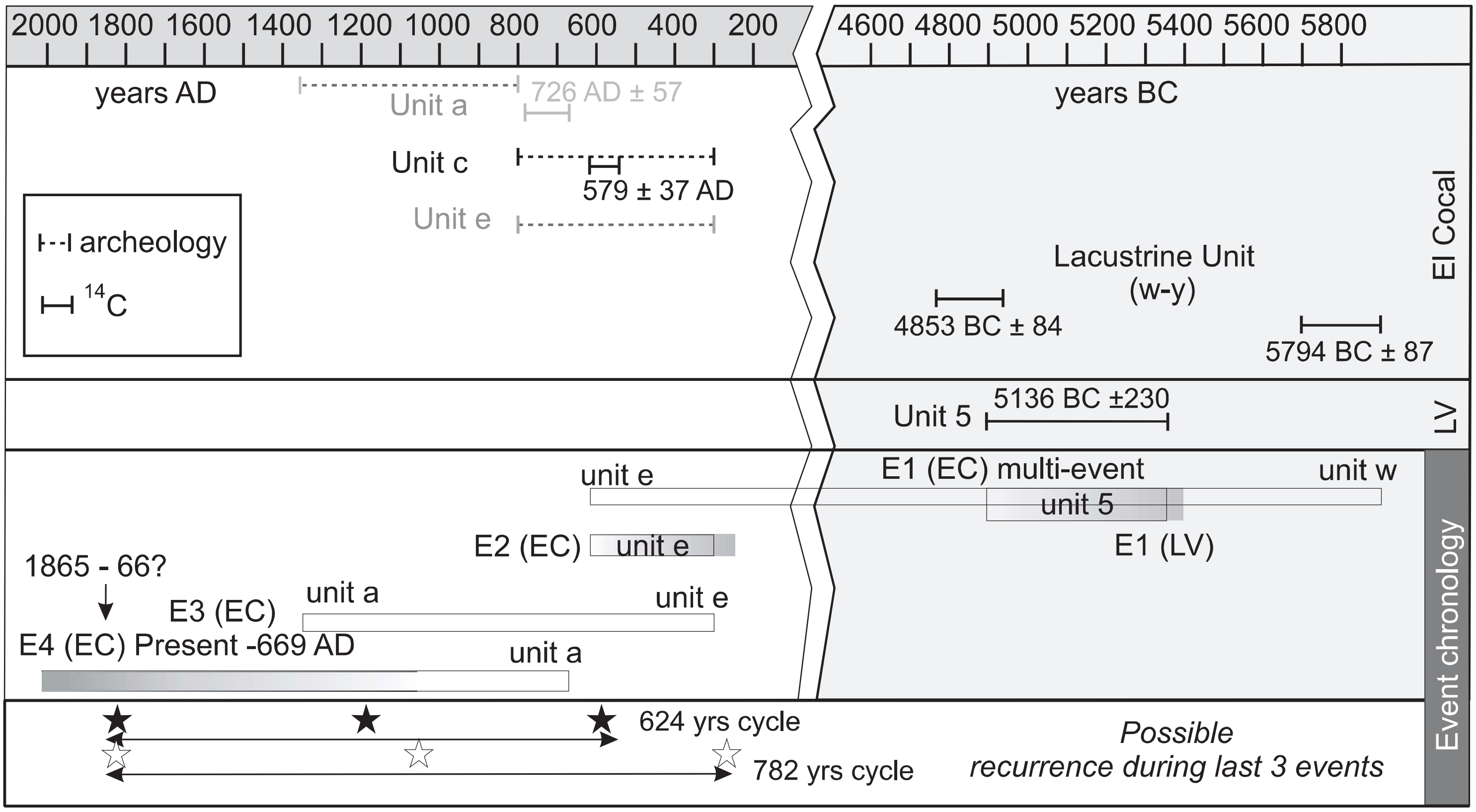

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Figure 4
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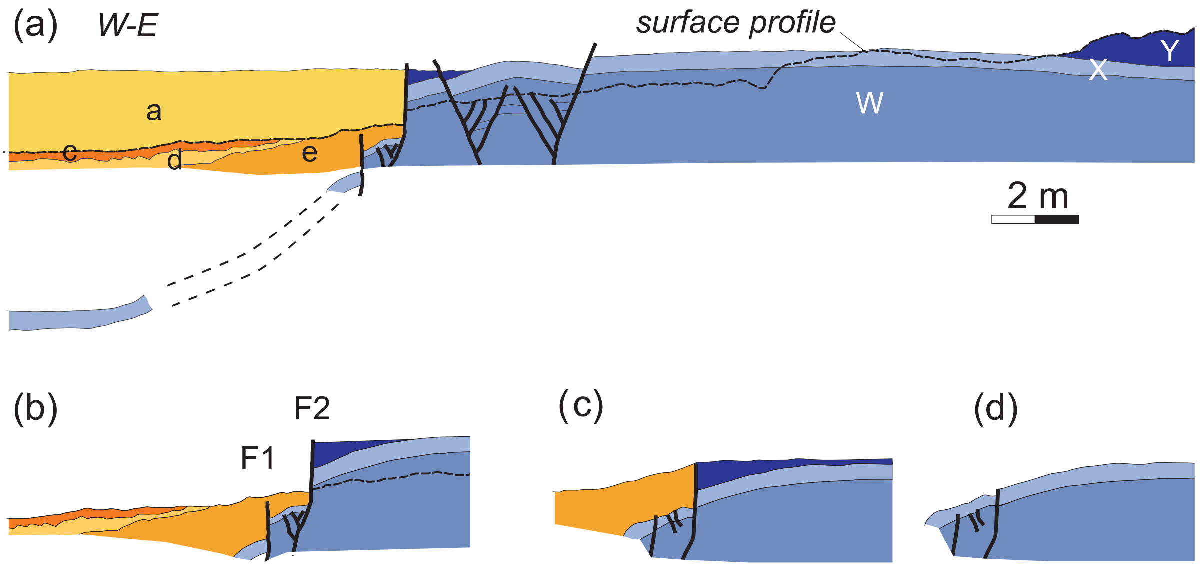

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Electronic Supplement

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

Authors: P. Santanach, P. Ruano, M. Ortuño, C. Rubí and E. Masana

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.

photomosaic El Cocal
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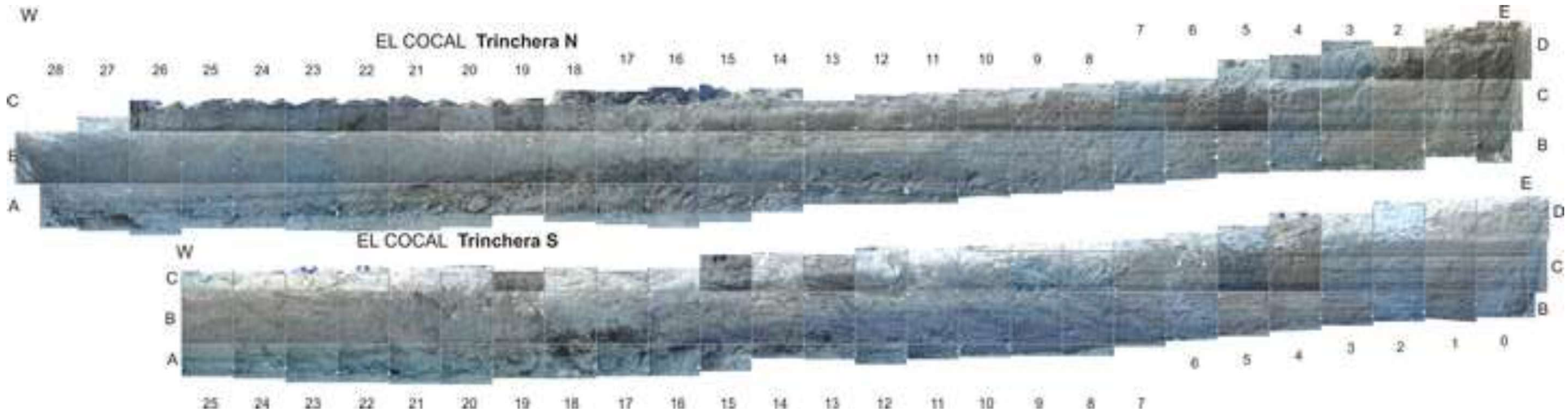
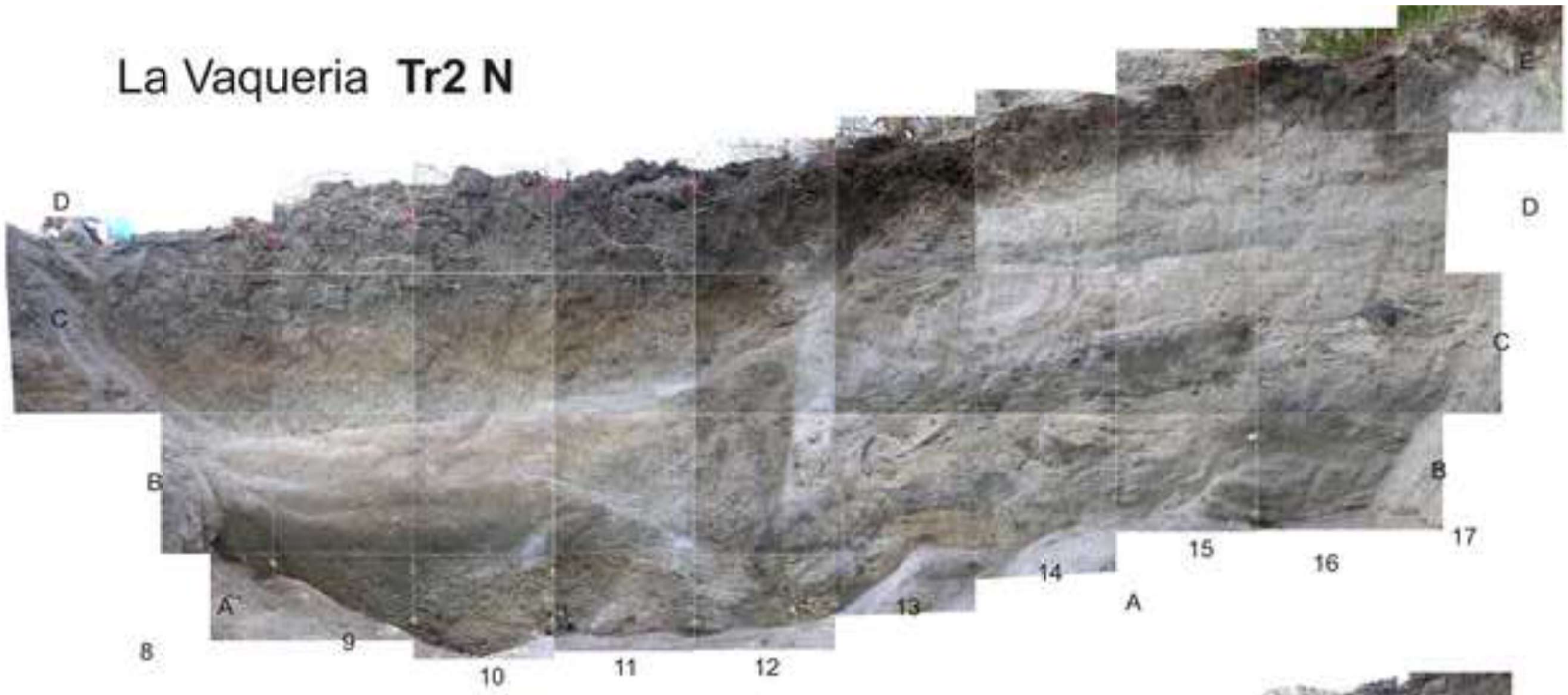
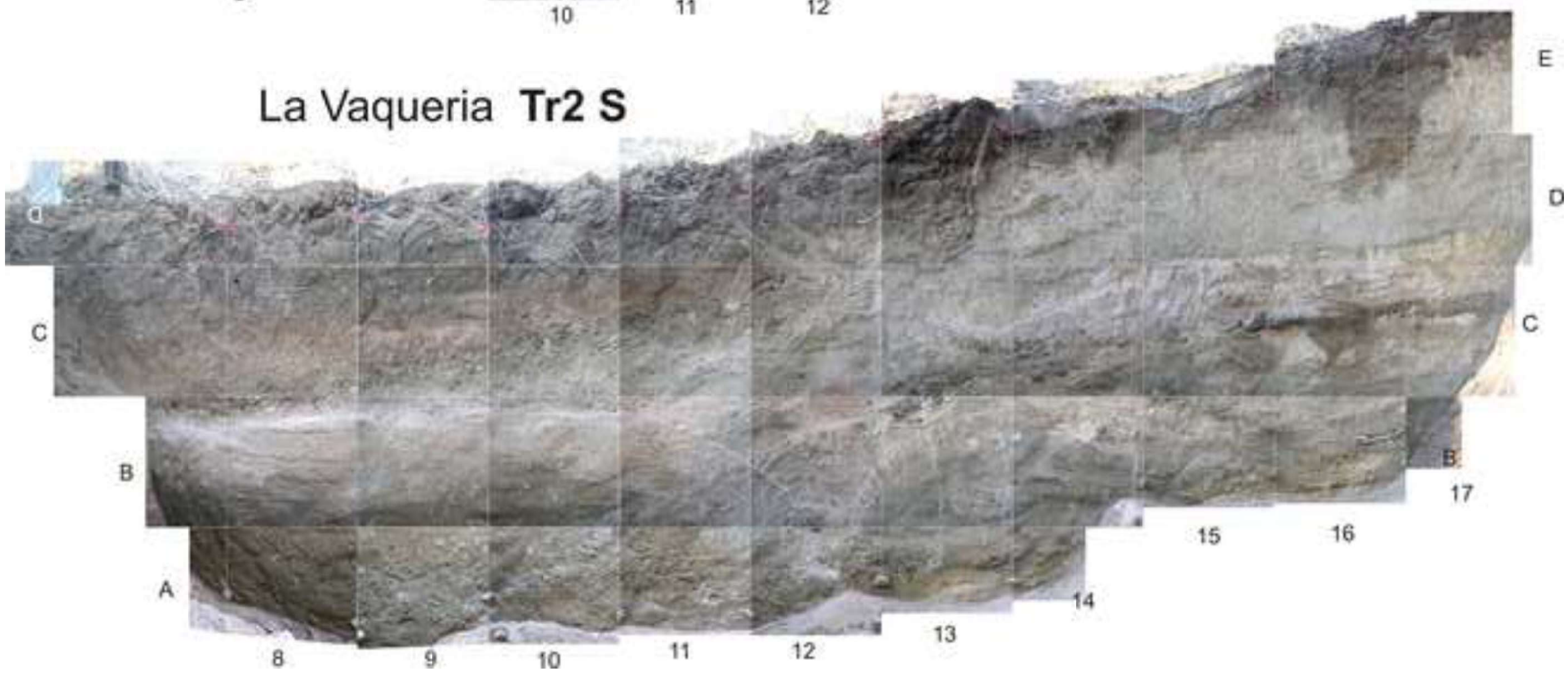


photomosaic La Vaqueria





photomosaic Piedra Menuda
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