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| Keyword: | Tree growth rings, Dendrochronology, Volcanic eruption, Pinus hartwegii, Tacaná |
| Is the invited manuscript for consideration in a Special Issue? : | Not applicable (regular submission) |
Evidence of volcanic activity in the growth rings of trees in the Tacaná Volcano, Mexico-Guatemala

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ABSTRACT

Volcanic activity can have a significant effect on the growth and survival of trees. The objective of our research was to analyze the effect of the volcanic eruption (1855/1856) of the Tacaná and evaluate the effects of the 1902 Santa María’s ash fall on the radial growth of trees of the Tacaná volcano. Dendrochronological sampling was carried out on sites covered by *Pinus hartwegii*, a ring-width chronology was built using 102 increment cores from 75 trees. The ring-width chronology shows two statistically significant suppression events, one of them occurred from 1857 to 1868 and was potentially caused by the historic eruption of the Tacaná (1855/1856). The second suppression event occurred from 1903 to 1908, where tree growth was affected 1 year after the Santa Maria volcano ash fall of 1902. The growth suppression did not have the same magnitude in all sampled trees, and it may be related to the thickness of the ash layer deposited around each tree. For the first time, we show that tree growth on Tacaná Volcano is reduced by ash fall from volcanic eruptions. Our results may contribute to the evaluation of risks associated with the volcanic activity of the Tacaná volcano.

Keywords: Tree growth rings; Dendrochronology; Volcanic eruption; *Pinus hartwegii*; Tacaná.
INTRODUCTION

Tree growth rings store evidence of natural phenomena and anthropogenic events. Thus, they are natural archives used to understand such events at broad temporal and spatial scales. Evidence of forest fires (Smith et al. 2016), extreme hydroclimatic events (D’Arrigo et al. 2008; Carlón Allende et al. 2016) and even volcanic activity (Krakauer and Randerson 2008; D’Arrigo et al. 2013; Seiler et al. 2017) has been detected in tree rings. Volcanic activity can have significant effects both locally and hemispherically through mechanical and meteorological events (Battipaglia et al. 2007; Legrande et al. 2016; Löffler et al. 2016). In addition to their geological and historical legacies, the evidence of these events may be seen in the morphology, dimensions, and stable isotopes of tree rings (LaMarche and Hirschboeck 1984; Minnis et al. 1993; Briffa et al. 1998; Stenchikov et al. 1998; Guillet et al. 2017). In most cases the effects are seen in the carbon balance of the tree, whether in reductions of the foliage quantity, the ability of the roots to take up water and nutrients, the length of the growing season, or the presence of stress related to high or low temperatures (LaMarche and Hirschboeck 1984; Seymour et al. 1983; Pieper et al. 2014). Consequently, trees exhibit reduced and asymmetric growth or even stop growing altogether (Biondi et al. 2003; Sheppard et al. 2009).

It has been observed that even a thin layer of ash (0.5 cm) can have a negative effect on the development of vegetation and the growth of trees (Seymour et al. 1983; Segura et al. 1995). This was dramatically illustrated during the 2018 catastrophic pyroclastic density flow from the Volcán de Fuego in Guatemala where a thin layer of ash was dispersed as far as Tapachula, Chiapas affecting the banana plantations (R. Velazquez; Personal communication, 2018). An extreme case of ash fall occurred during the 24 October, 1902 eruption of the Santa María volcano in Guatemala that produced a 28-km high Plinian
eruption that entered the stratosphere and was dispersed to the northwest by dominant winds into Mexico (Böse 1904; Williams and Self 1983). The estimated Dense Rock Equivalent volume of magma injected into the atmosphere was 8.5 km$^3$, which is why this is considered as one of the largest eruptions of the 20th century (Williams and Self 1983). The volcanic event generated a thin blanket of ash that covered southern Mexico, the Gulf of Mexico and the Pacific Ocean, while the Soconusco region, including the city of Tapachula and the Tacaná volcano in the state of Chiapas, were covered by 15-20 cm of a white-greenish layer of ash (Böse 1904). The ash layer from the 1902 eruption has been used as a stratigraphic marker to identify floods that occurred before and after 1902 (Sánchez-Núñez et al. 2012).

Regarding the historical eruption records of the Tacaná volcano, it has been mentioned that the earliest one took place in 1855/1856, but it has not been described accurately, other eruptions presented are phreatic explosions in 1949 and 1986 (Müllerried et al. 1951; Mercado and Rose 1992; Macías et al. 2009). These two recent explosions and their effects have attracted the attention of volcanologists who have assumed that previous eruption events must have had equal or greater destructive potential. Because of its eruptive record the Tacaná is considered as one of the most dangerous volcanoes in Mexico (Macías et al. 2015), particularly, because ca. 350 thousand people live within a 35 km radius from the volcano summit (Macías et al. 2010). Hence, tree ring analysis could serve as a proxy to identify the effects of earlier volcanic eruptions (Seiler et al. 2017) and to define the most dangerous areas near the volcano.

Therefore, the main objective of this research is twofold, first, to analyze the effect of the volcanic eruption (1855/1856) of the Tacaná and evaluate the effects of the 1902 Santa María’s ash fall on the radial growth of trees of the Tacaná volcano. This information
should provide new insights regarding the eruptive impacts of these two volcanic events, to understand the nature and distribution of their impacts, and suggest potential future hazards associated with this volcano.

MATERIALS AND METHODS

Study area

The Tacaná volcano is the highest peak in the State of Chiapas; it is one of the landmarks delimiting the international border between Mexico and Guatemala (Fig. 1). Over 75 km to the SE of the Tacaná, lies the Santa Maria which is a relatively young (~ 30,000 years) and tall (3,772 m) volcano. Both, Tacaná and Santa María volcanoes lie within the Central American Volcanic Arc (CAVA); a volcanic chain related to the subduction of the Cocos plate beneath the North American and Caribbean plates at the Middle American Trench forming a triple point junction in the region (Guzmán-Speziale et al. 1989; Garduño-Monroy et al. 2015). The CAVA runs parallel to the coast from western Panama to the Mexico-Guatemala border. The Tacaná volcano is part of the Tacaná Volcanic Complex (TVC), which consists of four volcanic structures that line up in a NE-SW direction. From the oldest to the youngest, is the Chichuj volcano (3,800 m), followed by the Tacaná (4,060 m), Las Ardillas dome (3,760 m), and the San Antonio volcano (3,700 m) (García-Palomo et al. 2006). During the past 2000 years, volcanic activity has been focused on the Tacaná and the San Antonio volcanoes (Macías et al. 2015). For example, an active fumarolic field occurs on the NE flank of the San Antonio volcano (Rouwet et al. 2009) and modern phreatic explosions have taken place on the crater rim of Tacaná.

The Tacaná is a semi-conical-shaped volcano with a 600-m-wide horseshoe-shaped crater open to the northwestern side. This crater originated in the late Pleistocene with a NW flank
collapse of Tacaná (Macías et al. 2010). Both the crater and the disrupted flank of the volcano were partially filled by lava flows and summit domes. The summit dome has a maximum elevation of 4,060 m with an inner base located at 3,970 m and surrounded by the horseshoe-shaped crater. According to Macías et al. (2010), the 1949 phreatic explosion occurred at the southern edge of this crater at an elevation of 3,907 m, while the 1986 phreatic explosion appeared at the base of the scar at an elevation of 3,600 m (Müllerried et al. 1951; De la Cruz-Reyna et al. 1989).

All small tributaries and main rivers (Suchiate, Coatán, and Cahaoacán) drain towards the Mexican side in their course towards the Pacific Ocean. This drainage network has formed huge sedimentary aprons of fluviatile and lahar origin (Macías et al. 2010). Predominant land cover near the Tacaná volcano is agricultural fields and induced pastures, high prairie-forest, mountain mesophilic forest, pine forest, oak-pine forest, and sacred fir forest.

**Dendrochronological sampling and sample processing**

Dendrochronological samples were collected from *Pinus hartwegii* trees located on the flanks around the Tacaná volcano, inside the crater and in the lower parts of the domes. The sampling sites were located mostly on the northeastern and southeastern external parts of the Tacaná crater at elevations ranging from 3,400 to 4,040 m (Fig. 1). The sampled trees were selected based on their apparent longevity and minimal anthropogenic disturbance, thus avoiding external noise and enhancing the hypothesized negative effect of the eruptions and/or ashfall events. In addition, sampling was focused on trees where ash accumulation was known. The sampling strategy consisted of extracting increment cores with a Hägloff Swedish borer (10-mm-diameter), perpendicularly to the stem and at breast height (2-3 cores per tree). We drilled 75 trees for a total sampling set of 160 cores. Only
102 cores (64%) were suitable for dating purposes. Increment cores were processed using sandpaper with progressive grain sizes from 80 up to 1200 grains cm\(^{-2}\) according to standard dendrochronological techniques (Stokes and Smiley 1996). The ring widths were measured using a Velmex measuring system at a resolution of 0.001 mm (Robinson and Evans 1980). Measuring errors and quality of dating were verified with the COFECHA software (Holmes 1983). Only the ring series that presented inter-correlation coefficients >0.328 (p<0.01) were used for dendrochronological purposes.

**Ring-width chronology of *P. hartwegii* and comparison with volcanic activity**

Tree growth varies over the lifespan of a tree. Such variation alters the shape of the raw – ring-width time-series, known as the age trend. For dendrochronological purposes, age trends are removed using standardizing methods depending on what growth information is needed (Cook and Kariukstis 1990). Thus, for standardizing purposes of the ring-width series from *P. hartwegii* cores, we used the dplR library package (Bunn et al. 2018). After standardization, the low-frequency variability of the raw time series was eliminated but the high-frequency variability was kept so that the reduced growth of Tacaná trees during the volcanic events of 1855/1856 and 1902, was preserved. We made a comparison of the chronology of volcanic activity events (1855/1856 and 1902), by performing a Superposed Epoch Analysis (SEA) (Lough and Fritts 1987). For both eruption events we chose a window length of 10 years, spanning from 5 years pre-event to 5 years post-event (Bunn et al. 2018; Mukund et al. 2019).

**RESULTS**

**Tree-ring chronology of *Pinus hartwegii***
The upper flanks of the Tacaná Volcanic Complex are irregularly covered by modern soil. Beneath this soil layer there is a layer of white fine ash from the 1902 eruption of the Santa María volcano (Fig. 2). Trees that were 237 years old (1780-2017) were found, however, only 34 out of 102 analyzed cores, contained the year 1855, and 76 included the year 1902. For these cores, abrupt decreases in ring-width were seen a year or two after the volcanic event (Fig. 3).

Other periods with reduced growth were seen from 1796 to 1799 and from 1810 to 1823. Above-average growth periods were detected from 1830 to 1838, 1980 to 1983, and 2003 to 2006. The earlier part of the chronology (1780-1830) showed higher variance attributed to a limited sample depth (<17 cores) (Fig. 3).

The dendrochronological parameters of *P. hartwegii* ring-width series indicated acceptable values for developing a ring-width chronology. The inter-series correlation (0.370) was higher than 0.328 (p<0.01) required by COFECHA to be considered properly dated, this species shows irregular growth with releases and suppression problems, producing frequent false and missing rings. Therefore, the inter-series correlation values are lower than 0.5. The mean sensitivity (0.101) has a positive value, which indicates that the series have a potential use in dendrochronology. The first-order autocorrelation (0.682), is also a common value for most of the conifer species in low latitude temperate forests; however, this autocorrelation disappears with the residual chronology.

**Volcanic signal in the growth rings of *P. hartwegii***

Not all dendrochronological series that included the 1855 and 1902 year showed decrease in ring width. We developed a chronology that clearly shows a decrease in width after the
eruptions of 1855/1856 and 1902 (Fig. 3). In our study, it was not possible to identify
growth suppression effects in the years 1949 and 1986.
The first growth suppression episode began in 1857 and continued up to 1868, the
reduction could be attributed to the volcanic eruption of 1855/1856, but the effect of this
event may have been delayed for a couple of years (Fig. 3). The comparison of the growth
rate for the rings from 1857 to 1868 with those from the previous decade (1847-1856)
suggests that the trees did not have suppressed growth before 1857. This growth reduction
began in 1857 but the maximum reduction occurred in 1862 (41% less than the average)
and between 1857-1868 (14% less than the average, Fig. 3 and Fig. 4a-b). The reduction in
growth after the 1855/1856 volcanic eruption was statistically significant (t-Student,
p<0.018) (Figs. 3, 4, and 5a-b).
The most important episode of growth suppression occurred from 1903 to 1912, in
comparison with previous years (1893 to 1902). This suggests that the trees did not have
suppressed growth before 1902. This growth was significantly reduced in 1903 (46% less
than the average) and during the period 1903-1908 (15% less than the average). The growth
suppression began in 1903 and continued on for several years (Fig. 4c and 4d, and 5). Thus,
tree growth in this area was significantly reduced after the eruption (t-test; p < 0.007)
probably as a result of the layer of ash that was deposited in the area (Figs. 3-5). However,
the 1902 ash layer did not maintain its original depth all over the TVC area because it may
have been removed from steep slopes by wind and rainfall, thus affecting the tree response
on radial growth.
The Superposed Epoch Analysis (SEA) showed that the ring width before the 1855/1856
eruption and the 1902 ash fall did not differ statistically (p > 0.05, p > 0.01) from the
average ring-width growth from 1850 to 1856 (Fig. 5a) and from 1897 to 1902 (Fig.6b).
However, the annual growth was severely reduced from 1857 to 1860 (year +2) (Fig. 5a), and in 1903 (year +1) after ash fall, (Fig. 5b). Thus, tree growth in this area was significantly affected only after the volcanic activity. Specifically, for the 1855/1856 event, the SEA shows that four years after the volcanic event tree growth was strongly affected by the volcanic eruption (reaching the maximum suppression point in the year +5) (Fig. 5a).

**DISCUSSION**

Growth rings can be extremely useful for dating volcanic eruptions due to their annual and seasonal resolution (Yamaguchi and Lawrence 1993; Sheppard et al. 2008; Seiler et al. 2017). Dating volcanic eruptions that occurred during the last centuries is usually done with isotopes (i.e. $^{40}\text{Ar}/^{39}\text{Ar}$, C-14) but the disadvantage is that the resolution may result in dating errors that may be displaced by 100 years (Noller et al. 2000). This is the case of the Tacaná volcano where dating of deposits has been mainly achieved by radiocarbon geochronology that constraints precise determination of late Holocene and historic eruptions some of which may not leave traceable deposits (Murcia and Macías 2014; Macías et al. 2019). Most of the trees located in the middle and lower parts of the Tacaná cone are young; this suggests that trees were recruited after recent disturbances caused by insect pests (bark beetles), forest fires or illegal logging. Above 3,400 m we were able to find and sample much older trees covering the last two centuries that may have been negatively affected by some of the recent and local volcanic eruptions. These local events not only included volcanic eruptions, but also hurricanes, earthquakes, floods, droughts, and landslides; these events represent high hazards and risks for the human settlements established on and around the volcano including the city of Tapachula, Chiapas (Mercado and Rose 1992; Murcia and Macías 2009; 2014).
The dendrochronological analysis of 102 increment cores of *P. hartwegii* of the Tacaná volcano dates back 237 years (1780-2017). Trees older than 200 years have witnessed volcanic-related events of Tacaná as the volcanic eruption reported in the year 1855/1856 by Böse (1904) and Mercado and Rose (1992); this eruption has not been well documented in terms of source, type, and magnitude of the event. This is not the case for the phreatic eruptions of 1949 (Müllerried 1951) and 1986 (De la Cruz-Reyna et al. 1989) where source and magnitude are precisely known. These explosions did not generate thick widespread ash deposits, but only localized deposits close to the venting sites. For this reason, the 1949 and 1986 events were not identified in the growth rings of our samples. Out of the 102 samples that were analyzed, 76 had the annual growth ring for 1902 (Fig. 3); however, the 1902 ash fall from the Santa Maria was only observed in 76.3% of the series (58 out of 76 series). As mentioned before, these differences might be related to the variation in thickness of the ash layer immediately after deposition and how long the ash was retained by the soil or by the vegetation (Segura et al. 1995). According to Böse (1904), the 1902 ash fell on the Tacaná left a 10-20 cm thick layer (Fig. 2). The ring-width chronology clearly shows a decline in tree growth after the years 1856 and 1902 (Fig. 3, and Fig. 5a and 5b). These effects in ring growth were not detected in chronologies developed 90 km away from the Tacaná volcano (Stahle et al. 2016) and in the Sierra de los Cuchumanates (Anchukaitis et al 2015). Similar results in ring growth suppression have been reported after the 1943 to 1952 eruption of the Paricutin volcano and the Tancítaro stratovolcano, both located in Central Mexico (Sheppard et al. 2009; Cerano Paredes et al. 2014) and from the 1913 eruption of Volcán de Fuego de Colima (Biondi et al. 2003).

Our results suggest that the growth suppression identified after 1902 resulted from diminished photosynthetic activity due to ash accumulation on the canopy of the trees.
This ash cover affects photosynthesis by (1) reducing the light reaching the chloroplasts and (2) by blocking the stomata and reducing the gas exchange between the plants and the atmosphere. Ash accumulation could also result in the physical damage of the stomata as reported in other volcanic eruptions (Seymour et al. 1983; Pieper et al. 2014). Strikingly, the effect of the 1902 ash blanket on the Tacaná volcano was not only found in 1903, but also in the eight subsequent years (Figs. 4 and Fig. 5b). This manifests that anomalous growth rings after the 1902 eruption are not due to low precipitation (because, wet conditions were reported after 1902; Fig. 6a modified from (Stahle et al. 2016) or to pathogenic factors but we consider this as evidence of the effect of the volcanic eruption of 1902. Despite identifying a major and significant effect on tree ring growth, no missing rings were identified in the years following ash deposition (Figs. 4 and 5). Thus, our results suggest that the influence of this volcanic event was moderate. This statement is based on the evaluation of volcanic eruptions using tree ring analysis that have usually found missing rings or micro-rings after volcanic eruptions (Biondi et al. 2003; Seiler et al. 2017).

Between 1857 and 1868, the chronology shows growth suppression effects which could be interpreted as evidence of a volcanic eruption (Fig. 5a) that apparently occurred in 1855/1856 as reported in historic documents (Böse 1904; Murcia and Macias 2009); if this eruption did occur, then it was larger in magnitude than the 1949 and 1986 phreatic explosions. We did not detect a narrow ring after 1857, which is why we believe that this eruption might have had a delayed effect on the growth of trees as it has been reported for other sites (Pieper et al. 2014).

Dendrovolcanic research based on the growth response of tree rings is still limited and has been focused mainly on documenting eruptions in stratovolcanoes (Yamaguchi and
Lawrence 1993; Biondi et al. 2003; Seiler et al. 2017), and much more limited for volcanic events that include ash fall that are relatively frequent events (Finch 1937; Eggler 1967). Notwithstanding dendrochronological research could provide useful information to determine the hazard and the associated risk of volcanic eruptions.

The width of tree rings could also be affected by meteorological (includes both weather and climate) or other external factors that occur at global and local scales. These factors are: weather variations, nutrient availability and local environmental conditions (Sheppard et al. 2001; Carlón Allende et al. 2018). However, our findings showed that growth suppression after 1856 was caused by an eruption of the Tacaná volcano (1855/1856) (Fig. 5a) and the growth suppression after the 1902 eruption of the Santa Maria Volcano was a response to heavy ash fall deposition and not due to meteorological factors (Fig. 6b). These growth suppressions following the 1855/1856 and 1902 events cannot be due to drought conditions, since this region experienced above average moisture (word includes both humidity, cloudiness, and precipitation) conditions (Stahle et al. 2016; http://drought.memphis.edu/MXDA/animation/Animation.aspx) (Fig. 6a and Fig. 6b).

CONCLUSIONS

By analyzing the tree ring growth of *Pinus hartwegii* on the upper slopes of the Tacaná volcano, we present, for the first time, evidence of the effects of the 1902 eruption of the Santa Maria volcano, Guatemala. The evidence was identified in 75 trees sampled at elevations between 3,400 and 4,060 m. The difference in the ring-width growth (suppression) after the year 1902 is convincing evidence of the deposition of ash on the top of the Tacaná volcano as no dry conditions were reported for that period. These data represent indirect evidence of the effects of ash deposition in paleoenvironmental archives.
The dendrochronological record also evidenced growth suppression of tree rings between 1857 and 1868 that may be associated to a historic eruption of the Tacaná volcano reported for the year 1855/1856. These results at Tacaná and other volcanoes in the region could help create a detailed tree-ring series associated with various geological hazards. Future research will expand the dendrochronological series to identify the effects of other volcanic eruptions in the TVC including dendrochemical analysis to determine the concentration of chemical components (e.i. Sulfur and Phosphorus) in the growth rings prior to and after the volcanic event. The results contribute with information that can be used to study hazards and risks associated to the TVC and other volcanoes present in the region.

ACKNOWLEDGEMENTS

The authors would like to thank the National Science and Technology Council for Project No. PN 522 assigned to J.L. Macías, and CONACyT-SENER-246911. M.E. Mendoza thanks PASPA-UNAM for his sabbatical grant. Special thanks go to G. Cisneros for technical work and to R. Vázquez for help during field expeditions. We would like to express our gratitude to two anonymous reviewers, and especially to Dr. Tom H. Hinckley for the detailed review of this manuscript, because their comments and suggestions allowed us to greatly improve the final version of this manuscript.
REFERENCES


Finch, R.H. 1851. A tree ring calendar for dating volcanic events at cinder cone, Lassen
National Park, California. Am. J. Sci. 5(33): 140–146. doi:10.2475/ajs.s5-33.194.140


Macías, J.L., Arce, J.L., García-Palomo, A., Mora, J.C., Layer, P.W., and Espíndola, J.M. 2010. Late-Pleistocene flank collapse triggered by dome growth at Tacaná volcano,


doi.org/10.1029/98JD00693


doi.org/10.1016/0377-0273(83)90083-5

Figures

Fig. 1. Location of the study site, a) Sketch of Mexico and location of the Chiapas state in southeastern México southeastern and western Guatemala, b) the State of Chiapas and the location of the Tacaná volcano in a green-red box, and c) Digital Elevation Model of the Tacaná Volcanic Complex (TVC) displaying the sites of dendrochronological sampling atop the Tacaná volcano either on the Mexico and Guatemalan sides.

Fig. 2. (a) Map of southern Mexico, Guatemala, and Belize showing the contour of five Isopachs (Furthest is >0 cm, 1, 10, 20, and 100 cm) of the 1902 ash fall layer dispersed during the Plinian eruption of the Santa María volcano (modified from Williams and Self, 1983), the eruption reached Villahermosa and Oaxaca, as well as, waters in the Pacific Ocean and the Gulf of Mexico, (b) Notice the irregular thickness of the 1902 white ash fall layer observed 1.2 km from the top the Tacaná volcano.

Fig. 3. Total ring-width standard chronology and sample depth (number of cores) of P. hartwegii of the Tacaná Volcano, the vertical gray boxes indicate years before and after 1856 and 1902, suppression in the 1903 tree ring growth is also shown.

Fig. 4. Common characteristics of growth rings from 1856 (a and b), and 1903 (c and d). Dendrochronological samples have a temporal resolution of 221 (a) and 177 years (c), the bark of both samples is on the right side, a) and c) include sequences of rings prior and after 1855 and 1902. A clear growth suppression is observed after the years 1902 and 1856.
Fig. 5. SEA charts showing the relationship between ring-width index and volcanic activity (year 0). a) Volcanic eruption reported in 1855/1856, b) Ash fall of October 1902. The horizontal lines in each panel mark significant departures based on bootstrapped confidence intervals (black dotted $p<0.05$; black solid $p<0.01$) for the period from 1780 to 2017.

Fig. 6. Palmer Drought Severity Index. After the 1855 eruption of the Tacaná volcano (a), and after the 1902 ash fall of the Santa María volcano, Guatemala (b) (Modified from Stahle et al. 2016; http://drought.memphis.edu/MXDA/animation/Animation.aspx).
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268x223mm (300 x 300 DPI)
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181x207mm (300 x 300 DPI)
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398x166mm (72 x 72 DPI)