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Tree-ring based reconstruction of rockfalls at Cofre de Perote volcano, Mexico

Osvaldo Franco-Ramos[a,*], Markus Stoffel[b,c], Lorenzo Vázquez-Selem[a]

[a] Instituto de Geografía, Universidad Nacional Autónoma de México, Ciudad Universitaria Coyoacán, 04510, Mexico
[b] Dendrolab.ch, Department of Earth Sciences, University of Geneva, 13 rue des Maraîchers, CH-1205 Geneva, Switzerland
[c] Climate Change and Impacts, Institute of Environmental Sciences, University of Geneva, 66 Boulevard Carl-Vogt, CH-1205 Geneva, Switzerland

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ABSTRACT

In this study, dendrogeomorphic techniques are employed to analyse the temporal frequency and spatial distribution of rockfalls on a talus slope of La Teta valley, located on the NW slopes of Cofre de Perote volcano at ~4000 m above sea level. Based on the interpretation of disturbance signals in growth rings of old-growth *Pinus hartwegii* Lindl. trees, we identify 100 growth disturbances related with rockfall events dated between 1780 and 2011, with slightly more than half of these events being dated to the last 50 years. The sectors most susceptible to rockfall correspond with the young rock lobes located at the foot of scarps. Roughly three in ten events has been triggered by regional, $M > 6$ earthquakes, whereas half of the events activity coincides with periods characterized by severe, prolonged summer rainfalls such as the ones occurred in 1995, 1998, 2005 and 2011.

1. Introduction

Mountains are areas of great geomorphic instability due to their steep slopes, sparse vegetation, enhanced seismicity and, in many cases, the impact of past and/or ongoing glacial and periglacial processes. These conditions favour the occurrence of instabilities and gravity-driven mass movements such as rockfall, snow avalanches, landslides and debris flows (Ritter et al., 1995; Shroder et al., 2013).

Rockfall is one of the most destructive processes for infrastructure and settlements at the foot or near mountain sides, as well as for visitors and hikers (Wieczorek and Snyder, 2004). Rockfall is described as the free falling, bouncing, and/or rolling of rocks and boulders of different sizes (usually < $5\ m^3$), originating from cliffs (over 45°) or rockwalls (Varnes, 1978; Erismann and Abele, 2001). Although inherently episodic in nature, rockfall is sufficiently frequent in many localities that, over even moderate time intervals, it can be regarded as a continuous process. The release of rocks and boulders is favoured by the alteration of bedrock on steep slopes and the related fracturing of rocks (Dorren, 2003). Rockfall material typically bounces and rolls down slopes in transit areas and tends to be deposited on more gentle slopes where it forms debris cones with semi-conical morphology and/or ramps and lobes at the foot of slopes (Luckman, 2004; Dorren et al., 2007). Rockfall also varies in size with volumes ranging from regular to considerable sizes of several million cubic meters, but smaller rockfalls ($< 10^1$ to $10^2\ m^{-3}$) are more frequent than bigger events (Luckman, 2004).

Different processes have been described to trigger rockfall activity, with earthquakes being the most frequent reason for the release of (larger) falls (Dorren, 2003; Keefer, 1984; Marzorati et al., 2002). Intense hydrometeorological events are yet another trigger of rockfalls (Cardinali et al., 2006; Schneuwly and Stoffel, 2008a, 2008b) as are freeze-thaw cycles (Matsuoka and Sakai, 1999; Stoffel et al., 2005a, 2005b). Whereas intense rainfalls and freeze-thaws cycles are typically responsible for smaller-scale, localized events, seismic triggering can occur over large areas and sometimes also induce larger-magnitude falls. For example, the $M = 6.9$ earthquake of 1989 in central California released rockfalls over large surfaces (Keefer, 2000), and even thousands of slopes were affected by rockfalls as a result of the $M = 7.3$ earthquake in Taiwan in 1999 (Khazai and Sitar, 2004). Where instabilities occur in densely populated areas, they may cause substantial damage, even more so if the occurrence of phenomena is poorly understood or not documented. This is the case in Central America where co-seismic landslides (including rockfalls) with $M > 6.5$ have repeatedly left hundreds of victims in the past (Bommer and Rodríguez, 2002). For the time being, for mountainous environments of central Mexico, general agreement exists that seismicity with $M > 6$ will likely generate landslides and threaten communities (Salazar-Salinas, 1922; Ramírez-Herrera et al., 2012), more in-depth knowledge on co-seismic mass movement activity is, by contrast, missing for Mexico and for the time being.

* Corresponding author.
E-mail address: ofranco@igg.unam.mx (O. Franco-Ramos).

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Tree damage has been repeatedly demonstrated to be a good indicator of contemporary dynamics of high-impact geomorphic activity. Studies of forest interaction with geomorphic processes goes back to the 1970s when Alestalo (1971) and Shroder (1978) started to employ disturbances in growth rings of trees to accurately date rockfall, debris flow, snow avalanche, and landslide activity (e.g., Butler and Stoffel, 2013; Stoffel and Corona, 2014).

Scars, callus tissue, tangential rows of traumatic resin ducts (TRD) and abrupt decreases in ring widths are the most frequent disturbances observed in trees affected by rockfall (Stoffel and Bollschweiler, 2008; Trappmann et al., 2013; Stoffel and Corona, 2014) and are frequently observed in rockfall-impacted trees. Dendrogeomorphic reconstructions have been employed in many mountain areas (Stoffel et al., 2005a, 2005b; Perret et al., 2006; Schneuwly and Stoffel, 2008a, 2008b; Schneuwly et al., 2009a, 2009b; Šilhán et al., 2013; Trappmann and Stoffel, 2012, 2015), and results of tree-ring based reconstructions have been used frequently to calibrate 3D rockfall process models (Stoffel et al., 2006; Corona et al., 2013; Trappmann et al., 2014). A review of dendrogeomorphic studies dealing with impacts of rocks on trees is provided in Stoffel (2006) and Trappmann et al. (2013).

Previous work in Mexico has demonstrated that some of the long-lived, subtropical conifer species growing at higher altitudes are forming well-defined annual increment rings, and that several species are thus suitable for dendrochronological purposes (e.g., Stahle et al., 2000; Villanueva Díaz et al., 2010). In spite of this, earth surface dynamics have only rarely been reconstructed with dendrogeomorphic techniques in the past. By way of example, Bollschweiler et al. (2010) and Franco-Ramos et al. (2013, 2016a, 2016b) have reconstructed lahar histories using tree-ring records of *Abies religiosa*, *Pinus ayacahuite*, *P. hartwegii* and *P. leyophilla* growing on the slopes of Popocatepetl, Volcan de Colima and La Malinche volcanoes (Mexico). Stoffel et al. (2011) also have shown that growth rings of *P. hartwegii* can be employed to record rockfall activity at the upper forest limit (~4000 m above sea level; hereafter a.s.l.) of Iztaccihuatl volcano.

Based on the encouraging results of previous studies, this study aims at (i) dating past rockfall activity on the talus slopes of La Teta valley, NW of Cofre de Perote volcano with dendrogeomorphic techniques; (ii) identifying major episodes of rockfall activity and their possible triggers; and at (iii) analyzing the temporal frequency and spatial distribution of events so as to identify process dynamics in the different areas of the study site.

2. Study area

Cofre de Perote (19°30′ N, 97°10′ W, 4282 m a.s.l.) is an inactive andesitic stratovolcano formed between ~1.3 and 0.2 million years ago. It is part of the Citlaltépetl-Cofre de Perote volcanic system, located at the eastern end of the Transmexican Volcanic Belt (Fig. 1A). The whole system is composed of stratovolcanoes, cinder cones and domes aligned NE-SW, dividing the Mexican Altiplano (Serdán-Oriental basin) from the coastal plains of the Gulf of Mexico. During the Pleistocene, these large volcanic edifices have been destabilized by strong earthquakes, intense fracturing, hydrothermal alteration, deglaciation, torrential rainfalls and – to a lesser extent – magmatic activity, which has in turn led to partial collapses of the system (Carrasco-Núñez et al., 2010).

Cofre de Perote is controlled by a system of faults and fractures (some of which are still active today) with preferential directions of NW–SE, N–S, and NE–SW, which coincide with the three volcanic structures Cerro Desconocido, Cofre de Perote and Las Lajas. Glaciation during the Late Pleistocene and Holocene favoured the formation of landforms and processes at Cofre de Perote, mainly at elevations > 3400 m a.s.l. (Fig. 1B) The glacial cirques, U-shaped valleys, moraines, as well as polished surfaces and scarps are still present on the present-day surface and frequently coincide with areas of increased instability (Carrasco-Núñez et al., 2006, 2010).

In addition, the steep slopes and hydrothermal alteration at their top have been found to promote landslide processes during strong ($M > 6$) earthquakes, especially at the SE slope of Cofre de Perote (Díaz Castellón et al., 2008). The upsurge of regional faults has generated significant earthquakes within the area; some of them have affected and destabilized Cofre de Perote. On January 3, 1920, major landslides and mudflows were reported on the SE slopes at Cofre de Perote along the Los Pescados river basin (Salazar-Salinas, 1922), and reportedly triggered by $M = 6.4$ seismic event with an epicentre at Quimixtlán, Puebla (25 km to the South). This event also caused major damage in the city of Xalapa, Veracruz (García Acosta and Suárez Reynoso, 1996). Another example is the $M = 7.3$ earthquake on August 28, 1973 (Figueroa, 1974), which caused damage in Tembladeras, located ~4 km NE of the summit of Cofre de Perote, and hundreds of victims in Serdan and Orizaba, Veracruz (Lugo and Inbar, 2002).

Meteorological data from Tembladeras station (CNA-SMN, 2013), located ~4 km NE of the study area at an altitude of 3102 m a.s.l., indicate a mean annual air temperature of 9.5 °C (mean monthly minimum 0.6 °C in February; mean monthly maximum 21 °C in May; for the reference period 1951–2010) and mean annual precipitation of 1708 mm (mean monthly minimum 33.3 mm in March; mean monthly maximum 346.5 mm in July). Rainy conditions prevail in summer (June to September), with maximum daily rainfalls ranging from 52 to 315 mm between 1951 and 2010. Some torrential rainfalls exceeding 100 mm in 24 h have been recorded on September 21, 1974 (315 mm), July 12, 1999 (200 mm), July 1, 2011 (160 mm; in this case within a few hours). On September 17, 2010, Hurricane Karl caused torrential rainfalls with a recorded 24-h total of 183 mm (CNA-SMN, 2013), thereby triggering major disasters on the SE slopes of Cofre de Perote. Between September 12 and 17, 2013, meteorological stations in the state of Veracruz recorded > 500 mm of rainfall during Hurricane Ingrid (CNA, 2013; Morales-Barrera and Rodríguez-Elizarrarás, 2014). Besides, the study region has been affected by winter snow in the past, as was the case for instance during the great snowstorm recorded between January 10 and 11, 1967 (Prieto-González et al., 2010).

In geomorphic terms, the study area is characterized by Holocene debris talus at the foot of the glacial La Teta valley headwalls, and located immediately to the east of the summit of Cofre de Perote volcano (Fig. 2A). The site investigated in this work covers an area of 0.26 km^2 with dominant slopes > 30°, and is composed of fallen blocks of different sizes, including large blocks of several cubic meters. Morphology of the talus is irregular, and different lobes were likely formed by different, yet large rockfall events. Evidence of recent rockfall activity is visible indirectly through the presence of decapitated trees (Fig. 2B), impacts scars on trunks (Fig. 2C) and candelabra-shaped trees (Fig. 2D), as well as via the fresh nature of some rocks on the present-day surface of the study site.

The forest covering the talus slope consists of *Pinus hartwegii* Lindl, a species that forms pure stands at the upper tree line at the highest mountains of central México around 4000 m a.s.l. (Lauer, 1978; Narave Flores and Taylor, 1997). *P. hartwegii* is also one of the oldest-growing conifers in Mexico, with evidence for trees over 400 years in age existing for Nevado de Colima (Biondi, 2001), Cofre de Perote (Villanueva Díaz et al., 2010), and Pico de Orizaba (Yocom and Fulé, 2012) volcanoes. However, strong anthropogenic pressure in central Mexico has endangered these old stands, although they are archives of climate information, geomorphic process activity, and of great ecological value (Villanueva Díaz et al., 2010).

3. Methods

At the study site, trees were sampled with increment borers and a chainsaw along three transects on the talus slope between 3860 and 4000 m a.s.l., immediately below the upper limit of the forest (Fig. 1C). To maximize spatial coverage of the analysis and to minimize tree selection based on visible (and therefore recent) defects, we performed

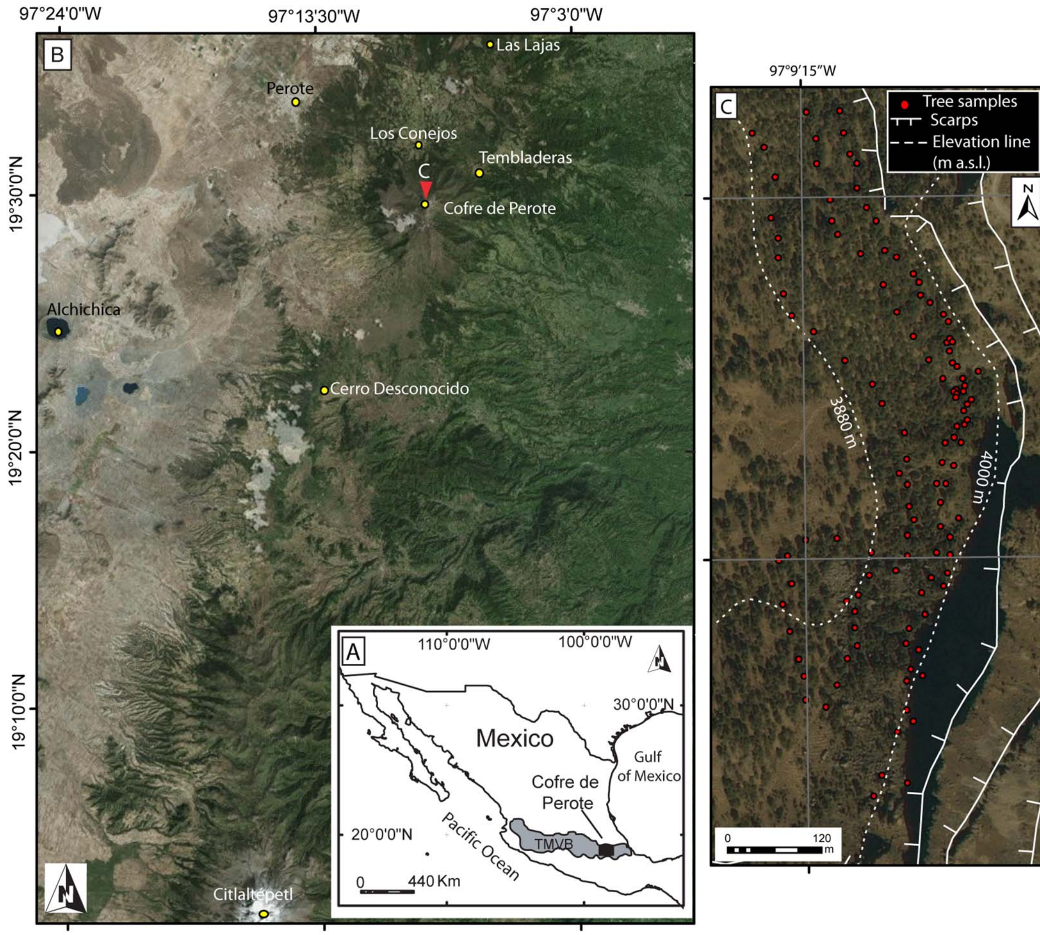

Fig. 1. Study area. (A) Map showing location of the eastern portion of the Transmexican Volcanic Belt. (B) Location of the study area at the foot of a talus slope of La Teta valley headwall on the NW slopes of Cofre de Perote volcano. (C) Locations of tree sample collection (red dots) close to timberline at 3860 m–4000 m above sea level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a randomized sampling and selected those *P. hartwegii* trees located closest to every 20-m step along a horizontal transect (Stoffel et al., 2013a). At each of these specific points along the transect, we then prioritized those trees with obvious rockfall damage such as scars, stem tilting, or decapitation. We sampled 110 trees, for a total of 200 increment cores, seven wedges (partial cross-sections) and five cross-sections (Fig. 3A,B).

Samples were prepared in the laboratory according to standard techniques described in Bräker (2002). After the dating of samples, ring widths were measured by means of a microscope and a sliding LINTAB measurement plate connected to a computer using the time series analysis software TSAPWin (Rinntech, 2012). To distinguish the influence of geomorphic disturbances and related impacts on tree-ring growth from the influence of climatic drivers, a local reference chronology was developed using samples from a nearby, but undisturbed site.

Analysis of rockfall impacts and related dendrogeomorphic anomalies focused on the identification and dating of scars following rockfall impact, abrupt growth depressions, reaction wood and callus tissue (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014). Disturbances in each tree were assessed according to the procedures described in Kogelnig-Mayer et al. (2011) and Stoffel and Corona (2014). In addition, the spatial distribution of years with reactions was studied using ArcGIS 9.2 following Stoffel et al. (2013a, 2013b). The chronology of rockfall events was compared with rainfall data from the meteorological station at Tembladeras (CNA-SMN, 2013), as well as with field and historical data on earthquakes (García Acosta and Suárez Reynoso, 1996; SSN, 2014).

Subsequently, trees with clear impact scars were selected for the elaboration of a map of rockfall recurrence periods. Following the approach described in Stoffel et al. (2005a, 2011), these recurrence intervals were obtained by dividing tree age at breast height by the number of impacts in each tree. The spatial analysis of data was performed with the Geostatistical Analyst module available in ArcGIS 9.2. Ordinary Kriging was used for the interpolation, considering the five nearest individuals and at least two trees in angular sections.

Noteworthy, most geomorphic processes tend to affect large surfaces (e.g., floods, debris flows, snow avalanches, and landslides), such that a single event will generally affect a large number of trees along its track. As a result, injuries and any other conventional type of GD can repeatedly be identified within a well-defined area and at the lower part of the trunk, as their distribution will be defined by the flow height of the process in question (Stoffel and Perret, 2006). In sharp contrast to the processes listed above, rockfall defined by the free or rebounding fall of individual or a limited number of superficial rockfall fragments from cliff faces, with volumes involved generally being < 5 m^3 (Berger et al., 2002). The release of volumes exceeding a few cubic meters remains exceptional and single rockfall fragments may, as a result, only disturb a limited number of trees along their trajectories, and are thus more difficult to be reconstructed with dendrogeomorphic techniques (Stoffel et al., 2013a; Stoffel and Corona, 2014). Therefore, and based on extensive experimental work (Stoffel and Hitz, 2008; Schneuwly et al., 2009a, 2009b, Trappmann and Stoffel, 2015), rockfall reconstructions are generally based on information contained in one or a few trees, and replication usually remains quite low. Provided that tree selection is done with sufficient care and that doubtful scars with

Fig. 2. Photographs of the study area. (A) Summit area of Cofre de Perote volcano with glacial La Teta valley headwall. The red arrow indicates deposits of recent rockfall activity. (B) Trees broken by large blocks. (C) Stem with a visible impact. (D) Decapitated trees forming candelabra growth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Photographs of analyzed trees. (A) Cross-sections of a tree with damage. (B) Core extraction with an increment borer from different sides of the trunk.

Table 1
Number and type of growth disturbances (GD) in *P. hartwegii* caused by rockfall in La Teta valley.

Growth disturbances (GD)	No.	%
Growth suppression	84	78
Injury	14	13
Callus tissue	8	7
Compression wood	2	2
Total	108	100

unusual morphologies are excluded from analysis, trustworthy results can still be obtained (Corona et al., 2013; Trappmann et al., 2013, 2014; Favillier et al., 2015; Morel et al., 2015).

4. Results

4.1. Tree age and growth disturbances

The 110 *P. hartwegii* trees analyzed in this study show an average age at breast height of 155 years with a standard deviation of 91 years. The oldest tree found at the site reached breast height in AD 1560, whereas the youngest individual had only 13 increment rings at the time of sample collection in AD 2011. The 212 tree-ring samples collected at the site exhibited 108 growth disturbances (GD) which could be attributed clearly to past rockfall activity (Table 1). A large majority of the GDs (78%) were in the form of sudden growth suppression, and 13% were clearly visible injuries; by contrast, callus tissue (7%) and compression wood (2%) were much more difficult to be found in the samples and/or much scarcer in occurrence.

Fig. 4 shows the distribution of minimum ages of trees within the study area. Younger trees, < 150 years old, are very much concentrated in the upper sections of the talus slope and near the most heavily disintegrated cliffs. In addition, younger trees (< 50 years) are typically concentrated in smaller areas, often in the form of patches and located within lobes, for which signs of (recent) rockfall activity is clearly present in the field. On the other hand, those parts of the stands where tree ages exceed 150 to 250 years are most frequently observed in the lower parts of the slope, and thus farther away from the rockfall-producing scarps. Interestingly, only a small number of trees has ages > 300 years; they are typically located near the bottom of La Teta valley, at ~3880 m a.s.l.

4.2. Reconstruction of rockfall events

Based on the nature (i.e. impact scars, callus tissue, tree decapitation and, partial stem burial, and candelabra-shaped trunks) and severity of GD observed at the site, we identify a total of 100 growth disturbances associated with rockfall events for the period 1780–2011 (Fig. 5), with a clear predominance of events over approximately the last 50 years (1960–2011). The most important events occurred in 1995, 1998, 2005 and 2011, with a total six, 14, seven and seven impacts, respectively. Another significant, yet much older event was observed in 1910 with 10 trees showing strong evidence of rockfall

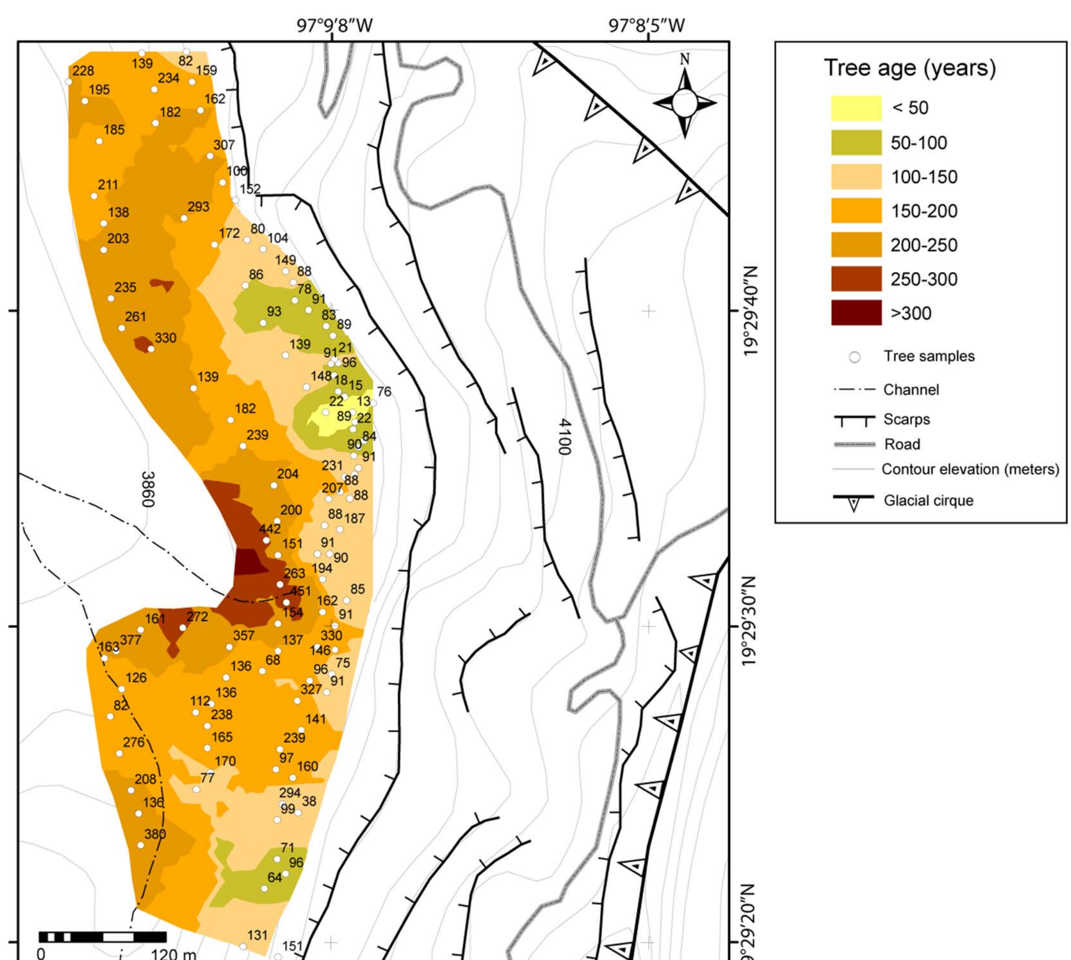

Fig. 4. Age interpolation of sampled *Pinus hartwegii* trees. Samples are usually taken at breast height: ~1.35 m. The age of trees varies, with younger trees predominantly located on unstable surfaces and near cliffs. The more stable sectors, usually located at the bottom of the talus slope, allow the survival of trees and favor longevity. Values next to dots indicate tree age estimates.

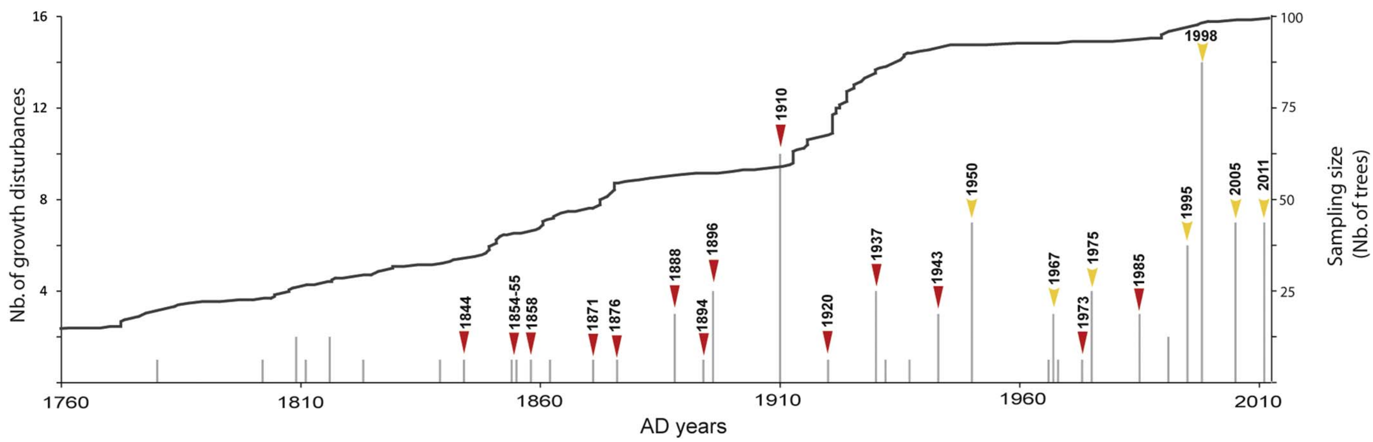

Fig. 5. Sample size (i.e. number of tree sampled) and number of rockfall events based on growth disturbances identified in samples from La Teta valley. Red arrow indicates the rockfalls related with $M > 6$ earthquakes. Yellow arrows show the rockfall triggered by torrential rainfall events related with hurricanes and tropical storms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

impacts. For the other rockfall events reconstructed at the site, replication was usually much smaller with one to three trees reacting simultaneously.

4.3. Return periods and spatial distribution of events

Return periods of rockfalls were assessed by dividing the number of impacts by the age of the impacted tree, yielding a mean interval of ~110 years between two impacts at the level of a single tree. The spatial interpolation of return periods is given in Fig. 6. Areas with the highest frequency of rockfalls coincide with the areas located nearest to the main escarpment; here trees are impacted at least once every 60 years. These areas coincide with the sectors characterized by unstable talus lobes, where young trees with recent impacts are dominating. By contrast, those sectors with the lowest rockfall frequency and thus the largest return periods between individual events, in the order of several centuries, coincide with those zones where older and more stable talus deposits exist, as well as with areas farther away from the escarpment, where trees tend to be more protected by the higher forest and/or morphological features (like lava ridges) from falling, bouncing and rolling rocks.

5. Discussion

In this contribution, growth-ring records of heavily impacted *Pinus hartwegii* trees have been used to reconstruct past rockfall activity on the talus slopes adjacent to vertical escarpments of La Teta valley, close to the summit of Cofre de Perote volcano (Mexico).

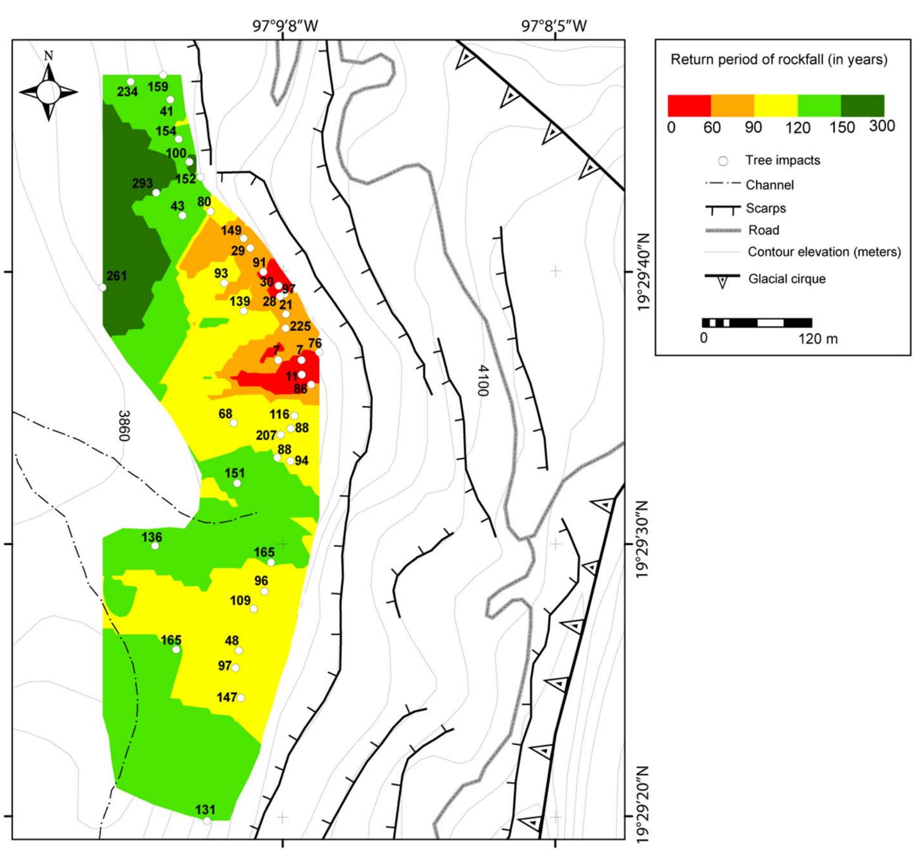

Fig. 6. Return period of rockfalls (in years) as obtained with the Ordinary Kriging method. Values next to dots indicate return period estimates for each of the trees sampled.

The reconstruction was based on a sampling along horizontal transects and consisted mainly in the extraction of increment cores. By contrast, only a very small set of wedges and cross-sections has been collected from trees showing clearly visible injuries.

Average ages of trees were assessed at breast height and show that *P. hartwegii* can easily live for several centuries at these high-elevation sites where they tend to colonize landforms with important geomorphic dynamics. In these highly active areas, *P. hartwegii* has competitive advantages over other more sensitive tree species (Stahle et al., 2000; Villanueva et al., 2015). Nevertheless, older trees (> 300 years) are typically located in areas that are less affected by rockfall, such as the foot the talus slopes and around old depositional lobes. However, as these sites typically hold a thin layer of stony soils, they can in turn favour enhanced water stress. These particularly harsh growth conditions may render the dating of old members often very complicated due to the abundance of extremely small rings (micro-rings), and sometime even missing or false rings. In the case of the more exposed sites near the cliff, where mostly younger trees (< 50 years) colonize the slopes under present-day conditions, growth and tree establishment is somewhat more limited by abundant soil instability as well as frequent rockfall activity. In addition, and considering the results of recent work by Stoffel et al. (2013a) or Šilhán et al. (2014), a mixed sampling of older and younger trees can guarantee that events of the recent past are represented in the reconstruction. This is because older trees have a reduced sensitivity to record impacts with increasing age, presumably as a result of the buffering effect of bark thickening in older trees (Stoffel, 2008) and the absence of rockfall-induced tangential rows of resin ducts (TRDs) in *Pinus* (Ballesteros et al., 2010a; 2010b). Following Stoffel and Perret (2006), we therefore decided not to select trees based on visible damage, as this would lead to an overestimation of the more recent activity and an underestimation of events farther back in time (Mayer et al., 2010), but to work with transects.

Rockfall also tends to be a discrete process typically affecting spatially limited surfaces and therefore does not (or only rarely) cause damage to large areas as is the case with snow avalanches (Stoffel et al., 2006; Corona et al., 2012), landslides (Lopez Saez et al., 2012a, 2012b) or debris flows (Bollschweiler and Stoffel, 2007, 2010; Bollschweiler et al., 2010). Trajectories of individual rocks are not therefore always clearly recognizable in the field as rocks may pass through forests with only few ground contacts. Trees located close or next to each other might be damaged by the same block, whereas other blocks may travel remarkable distances without impacting any trees (Dorren et al., 2007). The guidelines of Trappmann and Stoffel (2013, 2015) and Morel et al. (2015) have therefore avoided the sampling of multiple trees in a direct fall line, as shading effects will lead to an underestimation of activity (Trappmann et al., 2013).

In addition, the conservation of scars and anatomical anomalies in the tree-ring record will depend on the tree species (Trappmann et al., 2013; Trappmann and Stoffel, 2015), as wood and bark properties will cause differential vulnerability of trees to mechanical disturbance (Trappmann and Stoffel, 2013; Stoffel and Klinkmüller, 2013), and their wood and bark structures may mask scars at different rates and with varying efficiency (Stoffel, 2008). Conifers are known to overgrow injuries within years to decades, and the peeling of bark structures can completely blur evidence of injuries (Stoffel and Perret, 2006).

The issue of lacking evidence on the stem surface can be overcome (Stoffel et al., 2005a) by using the following GD as indicators of past rockfall activity: (i) abrupt suppression of tree growth indicating decapitation or branch loss; (ii) presence of callus tissue and tangential rows of traumatic resin ducts (TRD) around (blurred) injuries; and (iii) eccentric growth and the formation of reaction wood following stem tilting. The use of TRD has been proven most valuable for the detection and dating of past rockfall impacts in various conifer species (e.g., *Abies alba* Mill., *Larix decidua*, *Picea abies*, and *Pseudotsuga menziesii* (Mirbel) Franco) over the past decade or so (Stoffel et al., 2012; Stoffel and Corona, 2014). In the present study, the presence of growth suppression (78%), injuries (13%), callus tissue (7%), eccentric growth and reaction wood (2%) have greatly helped the identification of past rockfall activity. Reaction wood (compression wood) can only rarely be found in the tree-ring records of sampled *Pinus hartwegii* in La Teta valley. This can be explained by the predominance of scars, apex losses, branch removal or slight burial of stem bases by accumulation of scree. This observation is consistent with experimental work of Schneuwly et al. (2009a, 2009b) who reported a widespread lack of tilting in various European conifer tree species damaged by rockfall where impact energies can be very high but the shock will be rather short lived. Tree tilting (forming reaction wood), by contrast, is much more frequent in processes where pressure is exerted over longer periods of time (i.e. dozens of seconds to several minutes) and where erosion can destabilize the tree (Stoffel et al., 2013b) and/or where the root plate can be moved (Ballesteros al., 2015).Therefore, the formation of compression wood is much more commonly observed in trees affected by snow avalanches (Corona et al., 2010, 2012; Schläppy et al., 2014, 2016; Chiroiu et al., 2015), debris flows (Arbellay et al., 2010; 2010b; Mayer et al., 2010) and landslides (Lopez Saez et al., 2012a, 2012b).

By contrast, *Pinus* is known for its specific genetic make-up and the lack of TRD (Stoffel, 2008; Ballesteros et al., 2010a; 2010b). In combination with its thick bark preventing wood-penetrating wounds and the efficient blurring of scars, several authors have shown that a detection of past geomorphic evidence is often much more difficult in *Pinus* than in other conifers (e.g., Procter et al., 2011, 2012; Stoffel et al., 2011), which renders the detection of (older) events even more difficult.

Despite these limitations, we could reconstruct 100 rockfall events at the study site for the period 1780–2011, with just over half of the events dating to the last 50 years. This predominance of recent events is certainly due to the difficulty of identifying older events in tree-ring records but also reflecting the younger age of trees in those sectors of the slope where rockfall activity is more frequent (and thus also removing vegetation more frequently).

The comparison of those years with important rockfall activity with records on seismic events in the larger study area (e.g., García Acosta and Suárez Reynoso, 1996; SSN, 2014) and meteorological records from the Tembladeras station (CNA-SMN, 2013) indicate that a vast majority of the reconstructed rockfalls at La Teta indeed coincide with years having extreme meteorological or seismic events, and thus point to possible causal links between the processes.

By way of example, years with reconstructed, yet moderate rockfall activity (i.e., 1844, 1854, 1855, 1858, 1871, 1876, 1888, 1894, 1896, 1920, 1937, 1943, 1973 and 1985; see Fig. 5 for details) seem to coincide with regional, $M \geq 6$ earthquakes with epicentres located within 80 km from Cofre de Perote (e.g., in Veracruz, Jalapa, Orizaba, or Cordoba; García Acosta and Suárez Reynoso, 1996). In the case of the 1920 $M = 6.4$ earthquake, historical sources confirm the occurrence of major landslides and rockfalls on the SE slopes of Cofre de Perote (Salazar-Salinas, 1922) and thereby support the results of our study (Table 2). By contrast, we did not find significance rockfalls evidence in La Teta valley for the $M = 7.3$ earthquake of 1973, which destroyed part of the infrastructure of Tembladeras, a town located only ~4 km away from our study area, where it destroyed part of the town's infrastructure (Figueroa, 1974). Nevertheless, in 1910 a strong earthquake was recorded in Orizaba, Veracruz state (García Acosta and Suárez Reynoso, 1996). In this year, we identified growth disturbances on 10 damaged trees, possibly related with several rockfalls triggered by the earthquakes.

Interestingly, the largest number of GD occurred in 1950, 1967, 1975, 1995, 1998, 2005, and 2011, i.e. during years when massive torrential rainfalls were recorded at the study site (Table 2). These findings are in line with results from rockfall assessments realized in other mountain environments (Cardinali et al., 2006; Schneuwly and Stoffel, 2008a, 2008b), and point to the fact that several triggers may lead to the occurrence of larger rockfall events at a specific site.

Table 2
Rockfall events derived from dendrogeomorphic analysis and their relation with earthquakes activity and extreme rainfall events. Data sources: (a) García Acosta and Suárez Reynoso (1996); (b) SSN (http://www.ssn.unam.mx/). (c) Prieto-González et al. (2010). (d) Mexican Society of Seismic Engineering (http://www.smis.org.mx/). (e) USGS, Historical Earthquakes Database (http://earthquake.usgs.gov/earthquakes/). (f) Rainfall data from the meteorological station at Tembladeras (CNA-SMN, 2013) and hurricane and tropical storm data from NOAA (http://csc.noaa.gov/hurricanes/#).

Rockfall based on dendrogeomorphology (AD year)	Nb. of tree disturbances	Events on trees	Seismic record		(f) Meteorological date		
			Magnitude Richter scale	Localizated	Rainfall (mm)	Rainfall period in days	Hurricanes and tropical storms
1780	1	Loss of apex/branch	–	–	–	–	–
1802	1	Burial of stem base by block	–	–	–	–	–
1809	2	Burial of stem base by block	–	–	–	–	–
1811	1	Loss of apex/branch	–	–	–	–	–
1816	2	Burial of stem base by block	–	–	–	–	–
1823	1	Injury and burial of stem base by block	–	–	–	–	–
1839	1	Burial of stem base by block	–	–	–	–	–
1844	1	Loss of apex/branch	–	*(a) Strong earthquakes in several states of Mexico: Ver., Pue., DF., Oax., Gro., Zac., Mich., SLP., Qro., Mor., Jal., Gto., Ags.*	–	–	–
1854	1	Injury and burial of stem base by block	–	*(a) Strong earthquakes in D.F., Puebla., Jalapa, Orizaba, Cordoba y Ver. Ver.*	–	–	–
1855	1	Injury and burial of stem base by block	–	*(a) Earthquake in D.F., Atlixco, Pue., Jalapa, Orizaba y Cordoba, Ver.*	–	–	–
1858	1	Loss of apex/branch	–	*(a) Strong earthquakes en Jalapa, Cordoba,Teocelo, Ver. Puebla y D.F.*	–	–	–
1862	1	Loss of apex/branch	–	–	–	–	–
1871	1	Burial of stem base by block	–	*(a) Earthquake in Veracruz, Ver.*	–	–	
1876	1	Injury and burial of stem base by block	–	*(a) Light oscillatory earthquake in Cordoba, Ver., and Oaxaca.*	–	–	
1888	3	Loss of apex/branch	–	*(a) Several earthquakes in Orizaba Ver.*	–	–	
1894	1	Injury and loss of apex/branch	–	*(a)Several earthquakes in Orizaba Ver.*	–	–	
1896	4	Loss of apex/branch	–	*(a) Strong earthquakes in Jalapa, Ver.*	–	–	
1910	10	Injury and loss of apex/branch	–	*(a) Strong earthquakes in Orizaba, Ver.*	–	–	
1920	1	Injury and loss of apex/branch	6.4	(a) Xalapa great earthquake. 650 dead (epicentre in Quimixtlán, Puebla)	–	–	
1930	4	Burial of stem base by block	–	–	–	–	Tropical storm “no name”
1932	1	Burial of stem base by block	–	–	–	–	Tropical storm “No name”
1937	1	Loss of apex/branch	7.7	*(d) Earthquakes in Orizaba, Ver.*	–	–	
1943	3	Burial of stem base by block	6.7	(b) SE of Veracruz	–	–	
1950	6	Injury and loss of apex/branch	–	–	–	–	“ITEM” huricane
1966	1	Injury	–	–	120	1	Tropical storm “HALLIE”
1967	3	Loss of apex, burial of stem base by block	–	–	(c) Heavy snowfall in central and northern Mexico, with snow depths of tens of cm.		
1968	2	Burial of stem base by block, tilting	–	–	96	2	
1973	1	Injury	7.3–8.7	*(e) Strong earthquakes in Orizaba, Ver.*	146	2	
1975	4	Injury and burial of	–	–	244	2	Tropical depression “No

(continued on next page)

Table 2 (*continued*)

Rockfall based on dendrogeomorphology (AD year)	Nb. of tree disturbances	Events on trees	Seismic record		(f) Meteorological date		
			Magnitude Richter scale	Localizated	Rainfall (mm)	Rainfall period in days	Hurricanes and tropical storms
		stem base by block					name"
1985	3	Burial of stem base by block	8.2	*(b) Strong earthquakes in Central Mexico.*	165	1	
1991	2	Burial of stem base by block	–	–	112	1	
1995	6	Injury and burial of stem base by block	–	–	137	2	"ROXANNE" hurricane
1998	14	Injury and burial of stem base by block	–	–	110	2	
2005	7	Burial of stem base by block, tilting	–	–	120	1	Tropical storm "GERT"
2011	7	Injury and burial of stem base by block	–	–	342	3	Tropicales storms "NATE" y "ARLENE"
Total	100						

Noteworthy, all injuries and callus tissues related to these events were observed in the transition between the earlywood and the latewood, which is locally formed during summer in central Mexico (Biondi and Hartsough, 2010). As shown in Table 2, the timing of large rockfalls during these years coincides with the occurrence of intense summer rainfalls with > 100 mm over 24–48 h at the nearby meteorological station of Tembladeras, and that several of these large rainfall events were associated with hurricanes and/or tropical storms in the Gulf of Mexico.

By way of example, during the most recent rockfall event dated to 2011, an episode of extremely heavy rainfall was recorded in July as a result of the passage of the tropical storms Nate and Arlene in the Gulf of Mexico, with ~350 mm recorded within three days (Table 2). Hurricane Karl in 2010 caused abundant rainfalls around Cofre de Perote, and produced several slope instabilities, mainly on its SE slopes (Morales-Barrera and Rodríguez-Elizarrarás, 2014). During fieldwork in September 2011, some trees showed evidence of very recent scars but at heights of around 3–4 m, and therefore they could not be sampled. It is possible that (some of) these scars were inflicted by rockfalls triggered by the 2010 hurricane, but we do not have any proofs for this hypothesis.

Despite the somewhat limited number of rockfalls that we were able to reconstruct from growth-ring records of *P. hartwegii* trees and some limitations inherent to interpolations based on small event series, we remain confident that the spatio-temporal information we provide on rockfall dynamics can be of prime use for environmental and safety planning at Cofre de Perote National Park and other high mountains of central Mexico. Thanks to the annual resolution of the process reconstruction, and the extent of tree sampling in the field, we were able to obtain first insights into the frequency and spatial distribution of rockfalls along the talus slopes of La Teta valley. Furthermore, this study confirms the results obtained by Stoffel et al. (2011) in a similar setting and at the base of talus slopes of Iztaccíhuatl volcano, and underlines the real potential of *P. hartwegii* for space-time reconstructions of geomorphic process activity at altitudes around 4000 m a.s.l. within the northern Tropics. The connection between earthquakes and GD finally also highlights the potential of tree-ring studies to extend the seismic record around high mountains of central Mexico.

6. Conclusions

On the talus slope of La Teta valley, space-time relations of rockfalls have been reconstructed with the help of dendrogeomorphic methods. This contribution represents one in only very few studies focusing on high-resolution, long-term geomorphic dynamics at the upper limits of temperate forests on dormant volcanoes in central Mexico. Despite the difficulty of dating ancient trees and detecting signals for the more distant past, the forest at the study site represents an important natural archive to research the frequency and distribution of geomorphic processes or other environmental phenomena based on dendrochronology. The recent application of dendrogeomorphic techniques in temperate forests of Central Mexico can make a substantial contribution to the study of earth surface dynamics in a region where limitations or the lack of baseline information has often hindered in-depth analyses of geomorphic instability.

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