Journal of South American Earth Sciences 170 (2026) 105895

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Unusual number of large tectonic earthquakes before and during the birth of the Paricutin monogenetic volcano. Did they trigger, maintain, and boost the volcanic long-lasting activity from 1943 to 1952?

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A B S T R A C T

Volcanoes can be described as falling somewhere a large spectrum ranging from polygenetic systems, which are constructed through multiple, long-lived eruptive phases, to monogenetic systems, which usually form during a single eruptive event. Within this context, several decades of observations on Earth have shown that close and strong tectonic earthquakes can precede large eruptions of polygenetic volcanoes. In contrast, only a few close and large earthquakes have been reported before the birth of new monogenetic volcanoes, since the latter are rare. Here, we describe the unusually high number of large tectonic earthquakes that preceded the birth of the Paricutin monogenetic volcano in Mexico in 1943. Thirteen large tectonic earthquakes occurred in the near field during the 20-year period spanning the decade before the birth of Paricutin to the end of its eruption, whereas only one earthquake occurred within ten years after the eruption ended. This clustering of large tectonic earthquakes in space and time before and during the eruption of Paricutin is unusual for this region of Mexico. The significant difference in the number of tectonic earthquakes before, during, and after the eruption strongly suggests that Paricutin's birth and growth are related to these earthquakes. They may have changed the stress tensor near Paricutin's location, facilitating magma to migrate towards the surface and sustaining Paricutin's eruption for nine years - an unusually long period for a monogenetic volcano. We propose that changes in static and quasi-static stress fields, resulting from local faults, local tectonics, and static displacement fields generated by near-field earthquakes, may have triggered and boosted the Paricutin's eruption. In addition, we suggest that the dynamic stress field generated by the waves emitted by earthquakes may have altered magma pathways towards the surface prior to and during the Paricutin's eruption.

1. Introduction

For centuries, a correlation has been noted between earthquakes and the geophysical manifestations that occur during and after them. These manifestations include hydrological changes such as soil liquefaction, mud volcanoes, changes in stream flow and well levels, and activity in hot springs and geysers (Kuribayashi and Tatsuoka, 1975; King et al., 1999; Manga, 2001; Montgomery and Manga, 2003; Manga and Brodsky, 2006; Wang et al., 2006; Manga and Wang, 2007; Wang, 2007; Wang and Manga, 2010, 2021). Earthquakes can also trigger other earthquakes (Gomberg and Bodin, 1994; Stein, 1999) or volcanic eruptions (Darwin, 1838; Rockstroh, 1903; Yokoyama, 1971; Nakamura, 1975; Carr, 1977).

It is difficult to know who first mentioned the correlation between earthquakes and volcanic explosions. In Mexico, the earliest evidence of this correlation comes from pre-Hispanic pictograms on the Telleriano-Remensis codex, which reported 12 earthquakes and volcanic eruptions from 1460 to 1542 (Suárez and García-Acosta, 2021). For example, an earthquake was reported in 1507 (Fig. 1B), followed by a volcanic eruption in 1509 (Fig. 1C). Did the Aztecs establish a causal link between these two phenomena? It is unclear, but they did notice that both phenomena occurred in the same year or a few years apart, as they were depicted together.

One of the earliest written accounts was by Charles Darwin (1838), who attempted to provide physical explanations for these phenomena. Darwin described the effects of a large earthquake that occurred on February 20, 1835, which severely affected the city of Concepción in Chile. He mentioned that a submarine volcano near Juan Fernández Island and the Yantales volcano erupted that day. The Osorno and Corcovado volcanoes also erupted violently on the same day, on

This article is part of a special issue entitled: Active volcanoes of Mexico published in Journal of South American Earth Sciences.

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https://doi.org/10.1016/j.jsames.2025.105895
Received 1 October 2025; Received in revised form 21 November 2025; Accepted 28 November 2025
Available online 29 November 2025

November 11, 1835, and the Michinmahuida volcano had a significant explosion on December 5, 1835.

Nevertheless, it is difficult to prove that a large earthquake can trigger an eruption. It is well known that even a strong correlation between two phenomena does not establish a cause-and-effect relationship. This may explain why few scientific articles were published on this topic, particularly between the 1950s and the 1970s (Blot and Priam, 1963; Blot, 1964, 1965; Blot and Grover, 1967). However, many correlations were observed on Earth, raising the legitimate question of whether there is an actual cause-and-effect relationship between the two phenomena. Several articles mentioned such correlations again between the 1970s and the 1990s (e.g., Latter, 1971; Tokarev, 1971; Yokoyama, 1971; Ando, 1975; Nakamura, 1975; Carr, 1977; Yamashina and Nakamura, 1978; Gudmundsson and Saemundsson, 1980; Blot, 1981; Sharp et al., 1981; Acharya, 1982; Newhall and Dzurisin, 1988; Rikitake and Sato, 1989; Yokoyama and De la Cruz-Reyna, 1990; Nercessian et al., 1991; Marzocchi et al., 1993). In the 1990s, seismologists explained that earthquakes could trigger other earthquakes by the static stress changes following the Coulomb failure criterion (Hill et al., 1993; Gomberg and Bodin, 1994; King et al., 1994; Stein, 1999). This sparked renewed interest in the topic of earthquake-volcano triggering, particularly led by Dr. David Hill (Hill et al. 1995; 2002; Hill and Prejean, 2015; Prejean and Hill, 2018), who had worked on earthquakes triggered by other earthquakes. Some studies proposed that the triggering effects were caused by changes in static or dynamic stress, while other statistical studies suggested that the two phenomena are causally linked when considering all volcanoes on Earth (Barrientos, 1994; Hill et al. 1995; Linde and Sacks, 1998; Hill et al., 2002; Marzocchi, 2002; Marzocchi et al., 2002; Moran et al., 2004; Manga and Brodsky, 2006; Díez et al., 2005; Walter and Amelung, 2006, 2007; Walter, 2007; Walter et al., 2007; Eggert and Walter, 2009; Watt et al., 2009; De la Cruz-Reyna et al., 2010; Bebbington and Marzocchi, 2011; Bonali, 2013; Prejean and Haney, 2014; Takada and Fukushima, 2014; Hill and Prejean, 2015; Avouris et al., 2017; Kennedy, 2017; Nishimura, 2017, 2021; Prejean and Hill, 2018; Sawi and Manga, 2018; Gómez-Vasconcelos et al., 2020a; Seropian et al., 2021; Boulesteix et al., 2022; Nanjo et al., 2023). Nevertheless, this topic remains debated because some researchers firmly contest any kind of triggering causal relationship.

Most of the triggering eruptions mentioned in the literature involve polygenetic volcanoes. Very few cases of large earthquakes recorded before the birth of a new monogenetic volcano have been documented (Németh, 2025). Here, we present the case of Paricutin, a monogenetic volcano in Mexico, which was born in 1943. We show that 13 large, near-field subduction earthquakes occurred within a 20-year period spanning the decade before the birth of Paricutin to the end of its eruption. In contrast, only one earthquake occurred within the decade following the eruption.

2. The monogenetic Paricutin volcano

The Trans-Mexican Volcanic Belt is a volcanic arc associated with the subduction of the oceanic Cocos and Rivera plates beneath the continental North American Plate (Fig. 2). The Michoacán-Guanajuato Volcanic Field (MGVF), within the Trans-Mexican Volcanic Belt, is one of the highest concentrations of Holocene monogenetic volcanoes (black dots in Fig. 2) in a subduction context on Earth (Hasenaka and Carmichael, 1985a). It contains approximately 1565 monogenetic volcanoes and covers an area of approximately 40,000 km^2 (Hasenaka and Carmichael, 1985a; Hasenaka, 1994). The MGVF hosts two extinct polygenetic volcanoes: Tancítaro and Patamban (Ownby et al., 2007, blue triangles in Fig. 2). The MGVF comprises over 1100 scoria cones with associated lava flows, approximately 400 small-to-medium-sized shield volcanoes, around 22 phreatomagmatic vents (maars and tuff rings), around 43 lava domes, and isolated lava flows (e.g., Hasenaka and Carmichael, 1985a, 1987; Mahgoub et al., 2017). The monogenetic volcanoes of the MGVF are clustered both in space (Hasenaka and Carmichael, 1985b; Pérez-López et al., 2011) and in time (Mahgoub et al., 2017). The two most recent monogenetic volcanoes, Paricutin and Jorullo, are located near the Tancítaro volcano. Therefore, the next monogenetic volcano is likely to occur in this region (Larrea et al., 2019a, 2023), given the repetitive seismic swarms reported between 1997 and 2025 in the area between the Tancítaro and Paricutin volcanoes (Legrand et al., 2023; Caballero-Jiménez et al., 2024; Mendoza-Rosas et al., 2024; Perton et al., 2024, Servicio Sismologico Nacional: www.ssn.unam.mx).

Paricutin is the youngest monogenetic volcano of the MGVF. It is a scoria cone located only ~10 km northeast of the summit of Tancítaro. Born in a cornfield on February 20, 1943, it grew and remained active for nine years, until March 4, 1952 (e.g., Hasenaka and Carmichael, 1987; Lühr and Simkin, 1993; Guilbaud et al., 2009; De la Cruz-Reyna and Yokoyama, 2011). The eruption was closely monitored by national and international scientists, who provided geological maps, photographs, and collected samples throughout the nine years of activity (Lühr and Simkin, 1993). These unique datasets, complemented with eyewitness accounts (Foshag and González-Reyna, 1956), make Paricutin one of the best-documented historic monogenetic eruptions.

Paricutin's cone grew primarily during the first year of its activity (Fries, 1953; Lühr and Simkin, 1993; Larrea et al., 2017). It formed a

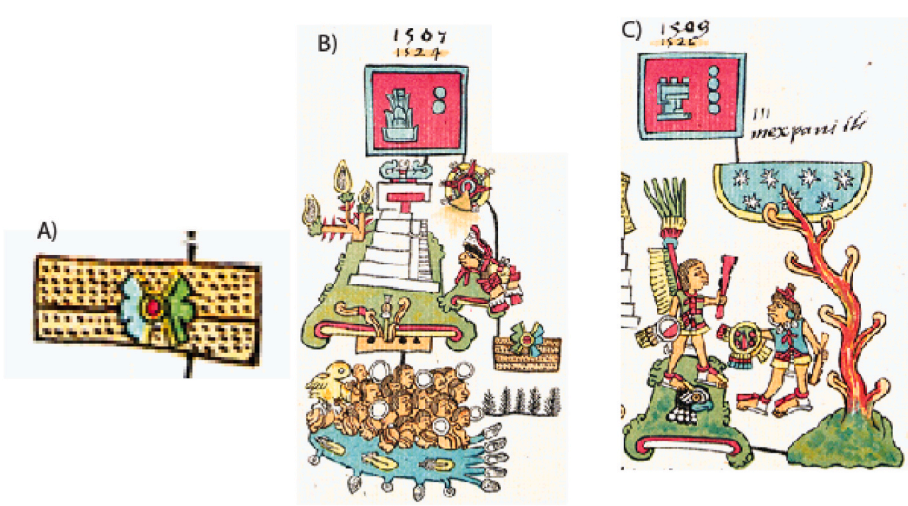

Fig. 1. Telleriano-Remensis Mexican Codices: A) The earthquake (tlalollin) is represented by at least two layers (tlalli) and a helix with a central eye (ollin). B) An earthquake occurred in 1507 and was represented here by four layers. C) Two years later, in 1509, there was a large volcanic eruption.

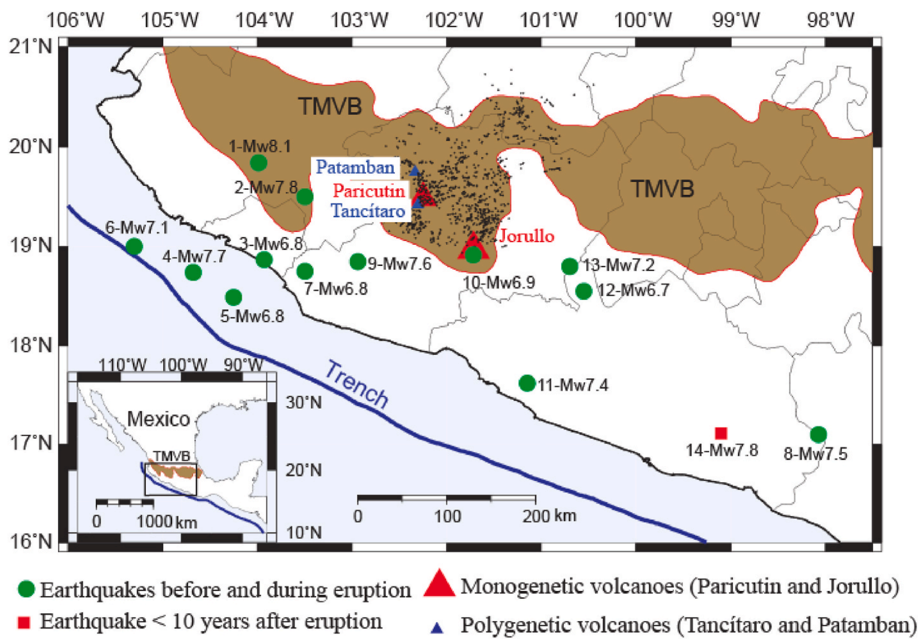

Fig. 2. Monogenetic volcanoes (black dots) within the Michoacán-Guanajuato volcanic field. The red triangles indicate the Paricutin and Jorullo monogenetic volcanoes. The blue triangles indicate the extinct, polygenetic Tancítaro and Patamban volcanoes. The brown area indicates the Trans-Mexican Volcanic Belt (TMVB). The green dots indicate the location of the near-field earthquakes that occurred in a 20-year period (1932–1952) before and during the eruption of Paricutin (1943–1952). The red square indicates the location of the near-field earthquake that occurred within a ten-year time window after the eruption ended. Earthquakes are listed in chronological order with green dots numbered from 1 to 13 in the 1932–1952 time window, preceding the magnitude Mw (the same as in Table 1) and red square numbered 14 for the earthquake that occurred in a 10-year time window after the eruption ended. The inset map in the lower left corner shows the location of the TMVB in central Mexico.

lava field covering ~25 km^2 with a volume of ~1.6 km^3 DRE (Larrea et al., 2017). Two adventive vents, Sapichu and Taqui, formed during the eruption and are aligned with the cone in a northeast-southwest direction (UNAM-IGEOL, 1945). Sapichu was active from October 18, 1943 to January 8, 1944. Four large explosions occurred during Paricutin's formation: on March 1, 1943; October 18, 1943; January 8, 1944; and February 1, 1952. The volcano's birth was sudden, lasting one or two days, described in the book by Foshag and González-Reyna (1956; Appendix FG1). Additional testimonies, quoted in Appendix FG2-4, indicate that Paricutin was indeed born on February 20, 1943. The cone grew rapidly, reaching 40 m high in one day, 165 m in two weeks, and 336 m in one year. Its base measured 560 m across within two weeks (McBirney et al., 1987; Lühr and Simkin, 1993). Paricutin's final elevation was 424 m in 1952. These classic numbers have been reevaluated: Paricutin built a main cone ~240 m high above the surrounding ground (~2800 m asl). The total cone elevation, including the current height and lava-buried base, is 430 m (Becerril et al., 2021).

Beyond its remarkable morphological development, Paricutin has also been central in advancing our understanding of magma evolution in monogenetic systems. Early petrological studies documented a progressive compositional change from olivine-bearing basaltic andesites to more evolved pyroxene-bearing andesites, a trend initially interpreted as the result of assimilation–fractional crystallization processes involving up to 20 % incorporation of granitic basement rocks (Wilcox, 1954; McBirney et al., 1987). This interpretation established Paricutin as a textbook example of crustal contamination in a subduction-related calc-alkaline suite. Subsequent work refined this view by linking distinct compositional stages to shifts in eruptive style and variations in isotopic signatures, further supporting the assimilation–fractional crystallization paradigm (Lühr, 2001; Erlund et al., 2010; Rowe et al., 2011).

However, more recent studies have challenged this classic interpretation. High-resolution analyses of major and trace elements, combined with Sr–Nd–Pb–Os isotopic data, indicate that the temporal and compositional variability throughout the nine years of activity is better explained by mantle source heterogeneities, magma recharge, and fractional crystallization, with little evidence for significant crustal assimilation (Larrea et al., 2019b, 2021). These studies further show that the eruptive sequence at Paricutin evolved from an initial short-lived system-opening stage - characterized by rapid dike propagation, transient conduit instability, and sharp shifts in magma composition (Albert et al., 2020), to a subsequent steady-state regime dominated by periodic magma recharge and more stable magma transport (Larrea et al., 2021). Thus, Paricutin not only provides an unparalleled record of the birth, growth, and decay of a monogenetic cone, but also remains a benchmark case for integrating morphological, geophysical, and geochemical observations into a dynamic model of magma plumbing system evolution.

The repeated seismic swarms between the Paricutin and Tancítaro volcanoes in 1997, 1999, 2000, 2006, 2020, and 2021, which stopped at a depth of 8 km, suggest that magma repeatedly attempted to reach the surface and that magma has been stored in the Earth's crust for several decades (Legrand et al., 2023). The stalled magma at a depth of ~8 km is comparable to the depth at which mineral equilibration was determined in petrological studies of volcanoes in the MGVF (Chevrel et al., 2016). These seismic swarms may reflect the presence of small, independent magma batches, as proposed by petrological and geochemical studies (Larrea et al., 2017, 2019b, 2021). Importantly, thermobarometric constraints for Paricutin itself indicate mid-crustal magma stagnation at <300 MPa (≈8–10 km), consistent with these geophysical observations and supporting the notion that magma repeatedly accumulates at similar depths before ascending or stalling (Larrea et al., 2021).They imply that there is no direct connection between the location of magma formation and the surface. They also imply that the next monogenetic volcano in the MGFV may emerge near these seismic swarms.

3. Large tectonic earthquakes before, during, and after Paricutin's birth

Lühr and Simkin (1993) studied the earthquakes that occurred near

Paricutin before and during the eruption. They distinguished between regional tectonic earthquakes, which originated in the trench, and local volcanic earthquakes, occurring near Paricutin. The researchers relied primarily on the only functioning seismometer at the time, located in Tacubaya, ~300–340 km from Paricutin. They used two criteria to distinguish between regional and local seismicity: (1) the distance of the earthquake, calculated from the difference in arrival times of P- and S-waves recorded in Tacubaya, and (2) a frequency criterion for P- and S-waves. Before the 1943 Paricutin's eruption, the researchers identified a series of local, moderate-magnitude (≤~4.5) volcanic earthquakes. Lühr and Simkin (1993) and Yokoyama and De la Cruz-Reyna (1990) primarily dealt with volcanic earthquakes, which are not the focus of our study. Here, we focused on regional and large tectonic earthquakes. Our aim is to study the effects of close and large earthquakes on Paricutin's volcanic activity.

People living near Paricutin reported feeling the large tectonic earthquakes that occurred before the 1943 eruption. In their book, Foshag and González-Reyna (1956) wrote:

Professor Ruperto Torres L., editor of a newspaper at Uruapan and a resident of that town for many years, related that some 2 years before the outbreak of Paricutin volcano, rather weak tremors were felt in the region. No particular significance was ascribed to them, since they were generally considered to be tectonic tremors with an origin in the Pacific Ocean, a not infrequent occurrence in the littoral of Colima, Michoacan, and Guerrero.

The large tectonic earthquake of February 22, 1943, with a magnitude of 7.4, was also strongly felt by the locals, only two days after the birth of Paricutin. This earthquake occurred 234 km from the volcano, a near-field earthquake at a distance about five times larger than the earthquake's size (index of 5, Table 1). Foshag and González-Reyna (1956) recounted Celedonio Gutiérrez's account of the earthquake in their book:

At 3 o'clock on the morning of Monday, the 22[d], there were earthquakes like we never had before. The earth shook for 7 or 8 min, with intervals of a few seconds. The people imagined that this was the ultimate agony of a great region.

4. Method and data

To select the tectonic earthquakes that may have affected the Paricutin eruption, we first need to define what constitutes an earthquake that is both "close" and "large" enough to potentially disrupt volcanic activity. To achieve this, we use the triggering index, TRIGI $=d/\sqrt{S}$, which is defined as the ratio of the distance "d" between the earthquake and the volcano, divided by the characteristic length $\sqrt{S}$ of the earthquake's rupture plane (Boulesteix et al., 2022; Legrand, 2022). S = L.W is the surface area of the rupture plane, where L is its length and W is its width. L and W depend on the focal mechanism and can be calculated using the following equations: $\log_{10}(L) = a_L + b_L.M_w$ and $\log_{10}(W) = a_W + b_W.Mw$, where a and b are constants that depend on the focal mechanism and Mw the moment magnitude (Blaser et al., 2010). For a reverse focal mechanism, $a_L = -2.28$; $b_L = 0.55$; $a_W = -1.8$; $b_W = 0.45$ (Blaser et al., 2010). This index delineates the boundary between "near-field" (values ≤ 10) and "far-field" (values > 10) distances. Hence, the distance of a near-field earthquake depends on its magnitude. Near-field earthquakes are expected to have a stronger effect on the volcanic activity through both static and dynamic triggering. At far-field distances, if earthquakes have any effect on the volcanic activity, it will only be through dynamic triggering.

Our initial catalog of earthquakes was compiled using data from the USGS (https://earthquake.usgs.gov/earthquakes/search/) and a list provided by Sawires et al. (2019). We calculated the TRIGI for all 6269 earthquakes with magnitudes greater than 4.0 between 1930 and 2020 in a region between −110°W and −96°W, 14°N and 23°N. We then selected the near-field earthquakes (with TRIGI ≤10). Although the post-eruption earthquakes did not affect the Paricutin eruption, we included them to provide a reference for background potential triggering seismicity felt at Paricutin. The 29 selected earthquakes are listed in Table 1 and shown in a histogram (Fig. 3), with bins of 10 years.

Table 1
List of near-field earthquakes of TRIGI ≤10 (USGS and Sawires et al., 2019) between 1930 and 2020. The main volcanic activity is reported.

#	Date	Mw	Latitude	Longitude	distance	TRIGI
1	03/06/1932	8.1	19.84	−103.99	182.59	1.78
2	18/06/1932	7.8	19.50	−103.50	125.69	1.74
3	25/07/1932	6.8	18.87	−103.93	181.49	7.92
4	21/09/1932	7.7	18.74	−104.68	260.94	4.04
5	07/12/1932	6.8	18.49	−104.25	229.34	10.01
6	30/11/1934	7.1	19.00	−105.30	318.06	9.83
7	29/06/1935	6.8	18.75	−103.50	146.21	6.38
8	23/12/1937	7.5	17.10	−98.07	516.24	10.07
9	15/04/1941	7.6	18.85	−102.94	92.25	1.60
10	20/06/1942	6.9	18.92	−101.72	83.47	3.25
	20/02/1943	Paricutin outburst				
11	22/02/1943	7.4	17.62	−101.15	234.42	5.13
	March 1943	More powerful activity with a 7 km high eruptive column, intense explosive activity took place from mid-March to early June 1943, generating large eruptive columns (2–6 km; Pioli et al., 2008) with fine ash deposition reaching as far as Mexico City (Fries, 1953).				
	18/10/1943 to 08/01/1944	Formation of Sapichu				
	08/01/1944 to 12/01/1945	Formation of the Taquí and Ahuan vents to the south and east of the main cone, respectively. During this time frame, extended violent Strombolian eruptions occurred and the activity at the main vent resumed, but with decreasing frequency				
12	21/04/1945	6.7	18.55	−100.55	208.36	10.20
13	03/10/1947	7.2	18.80	−100.70	182.17	5.02
	01/1945 to 02/1952	Irregular, short-lived lava flows, interrupted by Vulcanian explosions after 1949				
	04/03/1952	Last burst of activity				
14	28/07/1957	7.8	17.11	−99.10	424.88	5.87
	06/07/1964	7.3	18.14	−100.61	228.99	5.75
	30/01/1973	7.5	18.48	−102.99	127.45	2.49
	14/03/1979	7.6	17.81	−101.28	209.15	3.63
	25/10/1981	7.3	18.05	−102.08	154.53	3.79
	19/09/1985	8	18.19	−102.53	139.10	1.53
	21/09/1985	7.6	17.80	−101.65	192.98	3.35
	30/04/1986	7	18.40	−102.97	133.29	4.62
	09/10/1995	8	19.06	−104.21	203.71	2.23
	11/01/1997	7.2	18.22	−102.76	141.97	3.91
	22/05/1997	6.5	18.68	−101.60	110.21	6.80
	09/08/2000	6.5	18.20	−102.48	137.36	8.47
	22/01/2003	7.6	18.77	−104.10	202.55	3.52
	11/04/2011	6.5	18.23	−102.69	138.71	9.83
	18/04/2014	7.2	17.40	−100.97	265.40	7.31
	19/09/2022	7.6	18.46	−102.96	127.52	2.22
	22/09/2022	6.8	18.26	−102.96	145.94	6.37

Fig. 2 shows the 13 earthquakes that occurred before and during the Paricutin's eruption as green dots. The 14th earthquake, which occurred within 10 years after the eruption ended, is shown as a red square. Fig. 4a shows these 14 earthquakes with their corresponding magnitudes, and Fig. 4b shows them with their corresponding TRIGI index values. The closer an earthquake is to the volcano, the smaller its index value. The closer the earthquake to the volcano, the greater its potential impact on volcanic activity.

5. Discussion

5.1. An unusually large number of large tectonic earthquakes before the birth and during the growth of Paricutin

Fig. 3 shows the number of potential triggering earthquakes per decade between 1930 and 2020. Although the earthquakes that occurred after the eruption ended (1953–2020) had no effect on the

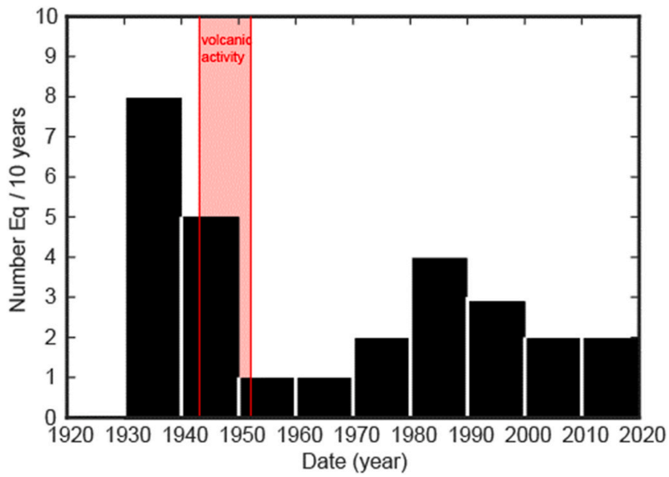

Fig. 3. Number of potential triggering earthquakes in the near field of Paricutin per decade, from 1930 to 2020. The red shaded area indicates the nine-year period during which Paricutin erupted, from 1943 to 1952.

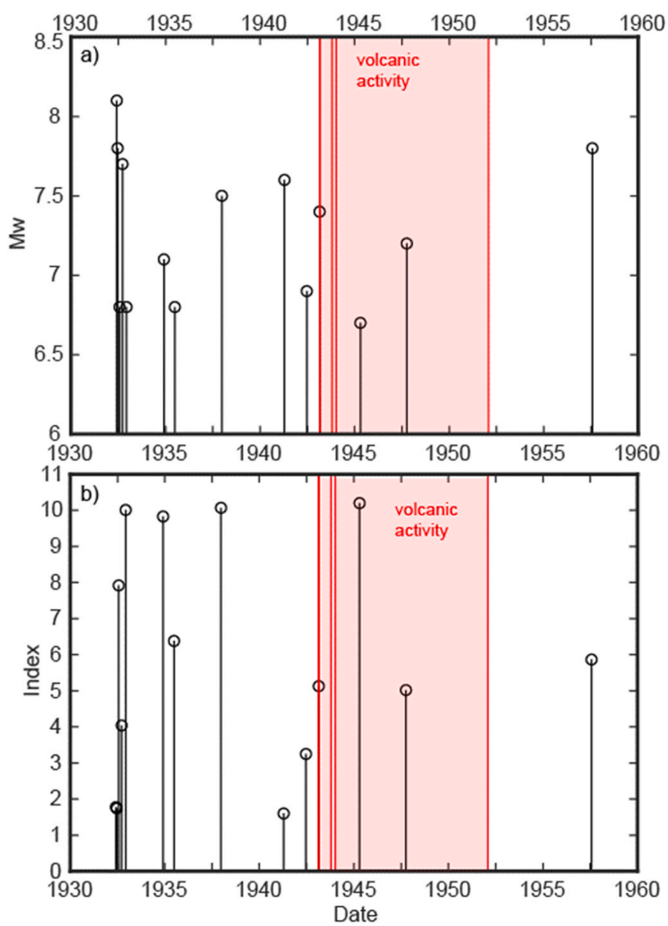

Fig. 4. (a) Temporal distribution of the magnitudes of tectonic earthquakes recorded at "near-field" distances (a distance ten times smaller than the characteristic length of the rupture fault) from Paricutin. They are potential triggering earthquake at Paricutin. (b) Temporal distribution of the TRIGI of these earthquakes. The closer an earthquake is to the volcano, the smaller its index value. The closer the earthquake is to the volcano, the greater its potential impact on volcanic activity. The red shaded areas represent the nine-year period of volcanic activity between the birth on February 20, 1943 and the death on March 4, 1952. The red lines correspond to the largest Paricutin explosions (see the list in the text and Table 1).

1943–1952 eruption of Paricutin, we included them to provide a broader context for the regional seismic activity that could have increased its duration and amplitude. The highest number of potentially triggering earthquakes (13) occurred during the two decades 1930–1950, i.e., before and throughout the nine-year eruption (1943–1952), except for the 1950–1952 interval, during which none occurred. Specifically, the number of earthquakes per decade before and during the eruption was eight (1930–1939) and five (1940–1949). After the eruption, seismicity decreased substantially, with only one to four events per decade (Fig. 3). This contrast allows us to characterize the pre- and syn-eruptive seismicity as unusually high for this region of Mexico. It is important to note that Paricutin is a monogenetic volcano and, therefore, will not erupt again. As a result, any post-eruptive seismicity, regardless of how small the corresponding TRIGI values may be, cannot trigger a new eruption at the Paricutin edifice. New monogenetic eruptions could indeed occur elsewhere within the Michoacán–Guanajuato Volcanic Field, but not at Paricutin itself. This interpretation is consistent with the recurrent seismic swarms that occurred between the Paricutin and Tancítaro volcanoes from 1997 to 2021, as previously mentioned. Of the ten near-field earthquakes that occurred in the decade before Paricutin was born (the green dots numbered 1 to 10 in Fig. 2), the two most recent ones (the green dots numbered 9 and 10 in Fig. 2) were particularly close to the future volcano. Because their TRIGI values were small (1.6 and 3.2, respectively, in Table 1), these earthquakes may have significantly perturbed the pre- and syn-eruptive system. The first earthquake (numbered 9 in Fig. 2) was a Mw7.6 thrust subduction earthquake that occurred on April 15, 1941, and was located 92 km from the current location of Paricutin. This earthquake occurred at a distance of 1.6 times the characteristic length of the earthquake rupture plane and took place about two years before the volcano's onset (Fig. 2). With the smallest TRIGI value of all the potential triggering earthquakes, this earthquake may have had a greater impact on the eruption onset than the others. The second (numbered 10 in Fig. 2) was the Mw6.9 earthquake on June 20, 1942, located 83 km from Paricutin. This corresponds to a distance 3.2 times larger than the characteristic length of the earthquake rupture plane. This earthquake occurred approximately eight months prior to the eruption (Table 1). These two earthquakes (numbered 9 and 10) occurred at near-field distances from the future volcano. In contrast, the other three near-field earthquakes (numbered 6 to 8 in Fig. 2), which occurred on November 30, 1934 (Mw7.1); June 29, 1935 (Mw6.8); and December 23, 1937 (Mw7.5) had substantially higher TRIGI values of 9.8; 6.4; and 10, respectively (Table 1). Owing to these higher TRIGI values, these three earthquakes (numbered 6 to 8) are considered less likely to have influenced the birth of Paricutin than the two earthquakes (numbered 9 and 10) that occurred within two years of the eruption. Note that a cluster of five earthquakes occurred within a six-month span from June to December 1932 (numbered 1 to 5 in Fig. 2), with magnitudes ranging from 6.8 to 8.1. The earthquakes on 3 and June 18, 1932 (numbered 1 and 2 in Table 1 and Fig. 2) had magnitudes of 8.1 and 7.8, respectively, and may have significantly perturbed the magmatic system due to their small TRIGI values of 1.78 and 1.74.

During the nine years of Paricutin's eruption, three near-field tectonic earthquakes occurred (green dots numbered 11 to 13 in Fig. 2 and Table 1), with magnitudes ranging Mw6.7 to 7.4. The largest Mw7.4 occurred on February 22, 1943, only two days after Paricutin's birth (numbered 11 in Fig. 2). This earthquake (numbered 11) was followed within weeks by a large explosion in March 1943 that produced a 7 km-high eruptive column and marked the onset of more vigorous volcanic activity. This earthquake numbered 11 occurred 234 km from the volcano, which is five times the characteristic length of the earthquake fault plane (i.e., also at a near-field distance, see Table 1). The second largest earthquake, with a magnitude Mw7.2 (numbered 13 in Fig. 2), occurred on October 3, 1947, 182 km from Paricutin. This distance is five times greater than the characteristic length of the earthquake fault plane, as for earthquake numbered 11 (Table 1).

The occurrence of such a high number of large tectonic earthquakes in a small region over a short time window (Fig. 3) is rare in this region of Mexico. In fact, no large tectonic earthquake occurred in the near-field during the five years after the eruption ended. In contrast, 13 near-field large tectonic earthquakes occurred within a 20-year period spanning the decade before the birth of Paricutin to the end of its eruption, whereas only one earthquake of magnitude Mw7.8 took place within ten years after its end, on July 28, 1957 (Table 1). These 13 large tectonic earthquakes occurred at an unusually high rate for the region, and they may have sustained Paricutin's activity for the previously described long-lasting nine-year period. Paricutin has already been cited as a notable example of a long-lasting eruption of a scoria cone (Pioli et al., 2008; Németh and Kereszturi, 2015), formed through violent Strombolian eruptions (Erlund et al., 2010). The volcano also produced an unusually large lava volume, now estimated between 1.59 and 1.68 km^3 DRE (Larrea et al., 2017), and showed marked temporal variations in magma compositions during the eruption (Larrea et al., 2017, 2019b, 2021). As highlighted by Larrea et al. (2017), not only magma composition and viscosity, but also volatile content and degassing dynamics played key roles in controlling explosivity (see also Parfitt and Wilson, 1995). Here, we propose an additional, external factor that may explain the prolonged eruption: the frequency of large, near-field tectonic earthquakes before and during the formation of Paricutin, which may have influenced the volcanic activity. The Paricutin's activity nearly coincided with the occurrence of large, near-field tectonic earthquakes and the end of the volcanic activity coincided with the end of the occurrence of large tectonic earthquakes. Similar links between regional earthquakes and volcanic activity have been suggested for other systems. For example, large earthquakes may have maintained, sustained and boosted eruptive activity at the polygenetic Popocatépetl volcano for around 30 years. During this time, intermittent periods of volcanic quiescence occurred in the absence of large tectonic earthquakes (Boulesteix et al., 2022).

5.2. Other cases of large earthquakes preceding the birth of a monogenetic volcano

The formation of new monogenetic volcanoes is an uncommon and typically poorly monitored phenomenon, given their short-lived eruptive histories and often unexpected onset. In contrast, flank eruptions on polygenetic volcano, frequently producing so-called "parasitic cone" are far more common (Sharp et al., 1981; Acocella and Neri, 2003; Yokoyama, 2015). These flank eruptions can generate monogenetic scoria cones (Németh and Kereszturi, 2015). Truly new monogenetic volcanoes born immediately after large earthquakes are even rarer. Sharp et al. (1981) suggested that large local and regional earthquakes are one of the mechanisms that trigger flank eruptions at the Etna volcano, which can generate parasitic cones. They suggested that these earthquakes can induce flank fracturing, changing the stress tensor with a tensile component and favoring flank eruptions. Another example of a parasitic cone is Volcancito, a lava dome formed on the flank of the polygenetic *Colima volcano* in Mexico during the significant eruption of 1869. Volcancito continued to erupt for eight years, until 1877, marking the end of its formation (Bretón et al., 2022). Volcancito is one of the many lateral volcanoes at the *Colima volcano*. Volcancito's birth was preceded by two large tectonic earthquakes on April 10, 1845 and June 19, 1858. It has been proposed that these earthquakes favored its formation (Bretón et al., 2022). The 1845 earthquake had an estimated magnitude of 8 and occurred in the state of Guerrero. The 1858 earthquake had an estimated magnitude of 8.0, and its epicenter was likely along the Michoacán coast, less than 400 km from Colima. The area of impact was similar to that of the 1985 earthquake (Bretón et al., 2022). We used the maximum possible distances for the 1845 and 1858 earthquakes, 500 km and 400 km, respectively. Even with these large distances, the TRIGI values are 5.5 and 4.4, respectively. These small TRIGI values ($\leq$10) indicate that these earthquakes occurred at near-field distances. Therefore, based on the TRIGI values, we agree with Bretón et al. (2022) that these earthquakes may indeed have influenced the birth of Volcancito. It is interesting that Volcancito also experienced several large tectonic earthquakes during its growth, similar to Paricutin. Bretón et al. (2022) wrote:

> On 2 November 1870, local chronicles reported "the earth shook with force even in the port of Manzanillo", located 60 km from the volcano. A year later, on 3 October 1871 a seismic series began. Between approximately 03:00 and 06:00 local time, there are reports of at least four strong earthquakes, the first of which included 5 s of shaking. Again, these events were felt as far away asManzanillo, and were strong enough to cause serious damage to buildings, some of which collapsed, although no casualties were reported. The largest of the events was described as "oscillated from north to south and lasted about one minute … This series of event occurred immediately before the reactivation of volcanic activity; however, whether it was a trigger or simply a consequence of pressure accumulation inside the magmatic system requires further consideration".

Yokoyama (2015) provided another example of an earthquake that occurred in Hokkaido, Japan, on June 17, 1973 with a magnitude of 7.4, approximately 140 km from the polygenetic Tyatya volcano in the Kuril Islands. The largest aftershock, with a magnitude of 7.1, occurred one week later, on 24 June. Approximately one month later, two parasitic vents formed on the flank of this volcano; the first on 14 July (northern flank of Tyatya) and the second on 16 July (southern flank). We calculated the TRIGI values of 3.1 and 4.3, respectively (assuming the aftershock occurred at the same distance from the volcano as the mainshock). Therefore, these earthquakes occurred at near-field distances from the volcano and may have influenced the formation of the two parasitic volcanoes.

Of course, monogenetic volcanoes can form without large tectonic earthquakes, as was the case in La Palma, where no near-field tectonic earthquakes occurred due to the local tectonics. Before the September 2021 Tajogaite (Cumbre Vieja) eruption, several volcanic seismic swarms were recorded, for example in October 2017 and February 2018, characterized by high b-values ($>>$ 1) of the Gutenberg-Richter law, suggesting the presence of magmatic fluids, and an impending eruption (Torres-González et al., 2020). But no large tectonic earthquake was recorded before the 2021 Tajogaite eruption.

5.3. How to prove the causal relationship between the Paricutin eruption and the selected earthquakes using seismic energy?

Proving a causal relationship between an eruption and a large earthquake is always challenging. Several studies have attempted to conduct statistical analyses using significant numbers of eruptions on both a local scale (Marzocchi et al., 1993; Marzocchi, 2002) and a global scale (Eggert and Walter, 2009). However, as Paricutin is a monogenetic volcano, it has only erupted once. Consequently, it is impossible to perform any statistical tests based on a single eruption. We therefore adopted an alternative approach to prove a causal relationship between the earthquakes and the Paricutin eruption. We compared the seismic energy density released by earthquakes related to the Paricutin volcano with that released by other polygenetic volcanoes. Here, we only consider earthquakes at near-field distances from Paricutin (TRIGI $\leq$10), as these are expected to have the greatest impact on the volcanic activity. Thus, the selection depends jointly on magnitude and distance; the earthquake must be strong enough and close enough to the volcano (see Table 1 for values). It is interesting to compare this graph of distance versus magnitude with graphs of other volcanoes. Fig. 5 shows the graph of Vanuatu volcanoes in the near field (Legrand et al., 2024), represented by black points. In Fig. 5, we included the 13 near-field earthquakes (green dots numbered 1 to 13 in Fig. 2) that occurred before the birth and during the growth of Paricutin, as well as the earthquake that happened after the eruption ended (red square

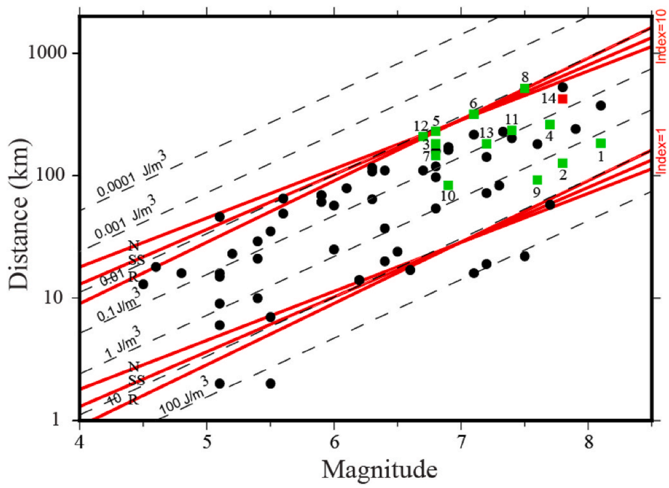

Fig. 5. Distribution of epicentral distance (in the near field, with an index TRIGI ≤10) versus magnitude, plotted on a $\log_{10}$-linear axis corresponding to the Vanuatu volcanoes (black dots) and the Paricutin volcano that occurred before the birth and during the eruption (green squares numbered 1 to 13) and the earthquake that happened after the eruption ended (red square numbered 14). Theoretical maximum distance curves (red lines) are added for normal (N), reverse (R), and strike-slip (SS) focal mechanisms for indexes of 10 and 1. The black dashed lines correspond to contours of constant seismic energy density e (in joules per cubic meter), ranging from 0.0001 to 100 J/m^3.

numbered 14 in Fig. 2). Fig. 5 also includes the lines corresponding to TRIGI 1 and 10 (near-field distances). To demonstrate that the concept of the near field primarily depends on the combination of magnitude and distance, rather than the focal mechanism, we plotted the curves corresponding to indexes 1 and 10 for the three main focal mechanisms (normal, reverse, and strike-slip). These curves are nearly identical for the two indexes of 1 and 10 (red lines in Fig. 5), confirming the independence from focal mechanisms.

Wang (2007) and Wang and Manga (2010, 2021) proposed the use of the maximum available seismic energy in a unit volume (called the seismic energy density e) as a general metric to explain the triggering effects, comparing it with laboratory measurements. Initially, they based an empirical relation relating e (in J/m^3), earthquake magnitude M, and epicentral distance r (in km) on strong ground motion data for southern California earthquakes (Wang, 2007):

$$log_{10}(e) = -3\,log_{10}(r) + 1.44M - 4.62 \quad (1)$$

The seismic energy density is approximately proportional to the square of the peak ground velocity (Wang et al., 2006), which in turn is proportional to the dynamic strain (Brodsky et al., 2003). Wang and Manga (2010, 2021) showed that some hydrologic changes require much greater seismic energy density, while others occur under very low seismic energy density.

To understand the triggering mechanism and quantify whether the seismic energy released by the earthquakes prior to Paricutin's eruption was sufficient to cause an eruption, we compared the seismic energy released at Paricutin and at other volcanoes around the world. We plotted the seismic energy density "e" (Equation (1)) for both the Paricutin volcano (green squares in Fig. 5) and the Vanuatu volcanoes (black dots in Fig. 5). Fig. 5 shows seven values of e ranging from 10^{-4} to 100 J/m^3. Most triggering of volcanic activity at Vanuatu volcanoes in the near field required a seismic energy density between 0.01 and 100 J/m^3, whereas at Paricutin, it ranged from 0.01 to 10 J/m^3. These values fall within the range of those found by Wang and Manga (2010), who found values ranging from ~10^{-4} to 10^4 J/m^3 for all hydrological responses, as well as values ranging from ~0.1 to 100 J/m^3 for magmatic eruptions. The seismic energy values calculated at Paricutin are within the range observed for other polygenetic volcanoes. These values strongly suggest that the birth and growth of Paricutin were actually triggered by the 13 earthquakes that occurred before and during the eruption.

5.4. *Dikes and earthquakes*

Magma can migrate towards the surface by using pre-existing faults or by generating new extensive fissures (e.g., Gómez-Vasconcelos et al., 2020b). Magma migration is sensitive to changes in the stress field produced by regional and/or local tectonics (Nakamura, 1977; Takada, 1994; Alaniz-Alvarez et al., 1998; Vespermann and Schmincke, 2000; Mazzarini et al., 2013a, 2013b; Martí et al., 2016). Stress field changes can be static, such as those imposed by local tectonics, or by the static displacement field generated by earthquakes, or can be dynamic, such as those caused by the passage of seismic waves generated by a large local or regional earthquake. Regional tectonic static stress fields usually control the orientation of dike intrusions (Martí et al., 2016). The static stress field generated by near-field earthquakes has more impact on volcanic activity than the dynamic stress field. However, we propose that dynamic stress field changes induced by an earthquake can also modify magma pathways before or during an eruption. In some cases, the direction of the dike may change due to a change in the stress tensor, such as that generated by an earthquake. Such direction changes were observed in seismic imaging of dikes during the 2020–2021 seismic swarm between the Paricutin and Tancítaro volcanoes (Perton et al., 2024). Before the January 28, 2020 Jamaica earthquake (M_w7.7), magma migration followed several pathways; afterwards, it became more focused along a single path (Perton et al., 2024).

This type of magma plumbing bifurcation has been observed in the field in the MGVF (Gómez-Vasconcelos et al., 2022), resulting in orthogonal or radial dike swarms that likely following preexisting fissure and fault systems. At shallow depths, dike intrusions may intersect preexisting faults, fractures, or lithological contacts as they rise toward the surface, especially when magma is overpressured. Even minor local shifts in the stress field, such as those caused by a large local or regional earthquake, can alter the feeding system by deviating the magma during its ascent. Such bifurcations may include minor deviations ranging from a few centimeters to several dozen meters, creating another dike, as seen at Paricutin (Fig. 6a) and other monogenetic volcanoes of the MGVF (Fig. 6b–d). If these bifurcations reach the surface, they can induce changes in eruption dynamics, with significant implications for volcanic hazard (Vespermann and Schmincke, 2000; Gómez-Vasconcelos et al., 2022). Note that two eruptive centers, El Astillero and El Pedregal, formed near Paricutin, to the south of the Tancítaro volcano, as a result of a change in vent and the generation of a new monogenetic volcano. They were accompanied by a change in magma composition and the formation of a new vent a few kilometres away (Larrea et al., 2019a, 2023).

It has also been observed that the geometry of Paricutin's vent and conduit changed during the eruption. Initially, two separate funnel-shaped vents aligned northeast-southwest were present, but by 1949–1951 only a single vent remained (Vespermann and Schmincke, 2000). Paricutin's feeder dikes exhibit northeast- and northwest-trending orientations, aligning parallel to the regional fault systems. We suggest that these changes may have been influenced by the three tectonic earthquakes in 1943 (M_w7.4), 1945 (M_w6.7), and 1947 (M_w7.2) that occurred during Paricutin's growth. While it is difficult to prove that such a phenomenon actually took place between 1943 and 1952, it is consistent with the observations made at depth during the 2020 seismic swarms southwest of Paricutin, following the Jamaica earthquake (Perton et al., 2024). Following the Mw 7.7 Jamaica earthquake on January 28, 2020, the earthquake swarm became more concentrated along a well-defined single fault between 29 and 31 January. A similar clustering of earthquakes was observed after the distant earthquakes on 6, 12, and 14 February. It was suggested that large earthquakes temporarily increased the pressure conditions,

Fig. 6. Magma plumbing bifurcation in the Michoacán-Guanajuato Volcanic Field. (a) Paricutin's early vent in the Mesa Los Hornitos in the southwestern part of the volcano, showing feeder dikes in northeastern and northwestern-trending orientations. b-d) Examples of dike bifurcations in various scoria cones within the Michoacán-Guanajuato Volcanic Field.

allowing the magma to migrate along a unique, localized path for at least several days (Perton et al., 2024).

6. Conclusion

We showed that, for Mexico, an unusually large number of 13 tectonic earthquakes occurred in the near field before and during the nine-year growth of the monogenetic Paricutin volcano. Within the two years prior to Paricutin's birth, two earthquakes occurred in the near field: one of magnitude 6.9 and the other of magnitude 7.6, at distances of 83 and 92 km, respectively, from the vent location. During Paricutin's nine-year growth period, three other tectonic earthquakes occurred in the near field, with magnitudes ranging from 6.7 to 7.4. The largest, of magnitude 7.4, occurred only two days after Paricutin's birth. In contrast, no near-field large tectonic earthquakes occurred near the volcano within five years after the eruption ended. In total, 13 large tectonic earthquakes occurred in the near field during the 20-year period spanning the decade before Paricutin's birth to the end of its eruption, while only one earthquake took place within ten years after the eruption ended. This high number of large tectonic earthquakes may have triggered, maintained and boosted the formation of Paricutin, resulting in the nine-year-long eruption. They may also be responsible for the observed bifurcation of the magma pathway towards the surface. We propose that changes in static and quasi-static stress fields, resulting from earthquakes occurring on local faults in the near-field could trigger and boost volcanic eruptions such as that of Paricutin. Furthermore, we suggest that the dynamic stress field generated by earthquakes could also change the direction of magma pathways towards the surface before and during Paricutin's eruption.

CRediT authorship contribution statement

D. Legrand: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Perton:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation. **M.G. Gómez-Vasconcelos:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation. **P. Larrea:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors have no conflict of interests.

Acknowledgment

We thank Denis-Ramón Avellán for the photos and the reviewers to improve the manuscript.

Appendix

Here are some quotations from the book of Foshag and González-Reyna (1956):

FG1:

Demetrio Toral, a laborer from Paricutin employed by Pulido as helper, was plowing land at Cuiyusuru. He had just completed a furrow and was about to turn his plow when the first outbreak of the volcano occurred almost in the exact furrow he had just drawn. This remarkable circumstance has led some people into the belief that Toral

"plowed up the volcano." Toral, a deaf mute, died soon after in Caltzontzin.

Before January 1943 nothing unusual about his (Dionisio Pulido) farm attracted his attention … Never, not even on the day of the initial volcanic outbreak on Cuiyusuru, did he note any unusual warmth in the ground, as has been so frequently stated in popular accounts of the event.

On February 20, 1943, Pulido left his village, going to his farm to prepare the fields for the spring sowing. He was accompanied by his wife, Paula, his small son, who would watch the sheep, and Demetrio Toral, his helper, to begin the plowing. The day was calm, and the sky was clear. Pulido's account, as he related it to us, follows:

"In the afternoon I joined my wife and son, who were watching the sheep, and inquired if anything new had occurred, since for 2 weeks we had felt strong tremors in the region. Paula replied, yes, that she had heard noise and thunder underground. Scarcely had she finished speaking when I, myself, heard a noise, like thunder during a rainstorm, but I could not explain it, for the sky above was clear and the day was so peaceful, as it is in February. At 4 p. m. I left my wife to set fire to a pile of branches which Demetrio and I and another, whose name I cannot remember, had gathered. I went to burn the branches when I noticed that a cueva, which was situated on one of the knolls of my farm, had opened, and I noticed that this fissure, as I followed it with my eye, was long and passed from where I stood, through the hole, and continued in the direction of Cerro de Canicjuata, where Canicjuata joins Mesa de Cocjarao. Here is something new and strange, thought I, and I searched the ground for marks to see whether or not it had opened in the night, but could find none; and I saw that it was a kind of fissure that had only a depth of half a meter. I set about to ignite the branches again when I felt a thunder, the trees trembled, and I turned to speak to Paula; and it was then I saw how, in the hole, the ground swelled and raised itself 2 or $2^{1/2}$ m high, and a kind of smoke or fine dustgray, like ashes-began to rise up in a portion of the crack that I had not previously seen near the resumidero. Immediately more smoke began to rise, with a hiss or whistle, loud and continuous; and there was a smell of sulfur. I then became greatly frightened and tried to help unyoke one of the ox teams. I hardly knew what to do, so stunned was I before this, not knowing what to think or what to do and not able to find my wife or my son or my animals … I saw that there was no longer any water in the spring, for it was near the fissure, and I thought the water was lost because of the fissure."

FG2:

On the following day Pulido drove his oxen to the forest to graze and then went to his farm to see what had occurred. When he arrived there at 8 a.m., he saw that a hill, which he estimated to be 10 m high, had formed and that this mound emitted smoke and hurled out rocks with great violence.

Alfonso de la 0. Carreño (1943) states that a light seism accompanied by subterranean noises and followed by a distant detonation was perceived at San Juan Parangaricutiro on Saturday, the 20th, at 5:20 p. m. Pulido reported to him that, at 4 p. m. and before, he walked about his farm hearing noises like those of a heavy freshet, that the sky was cloudless, and that he looked in all directions to localize the noise. Then suddenly he saw a large column of black smoke arise from a depression, and a fissure, 5 cm wide, open in the soil; and he was able to follow the eastward-trending fissure with his eye for 30 m.

Paula Cervantes Rangel de Pulido, wife of Dionisio Pulido, …spent part of the day in the shade of an oak, watching the sheep grazing on the sparse herbage. As the sheep moved on she changed her position to another nearby tree, and it was from there that she saw a small whirling dust column (remolinito) follow a small fissure in the soil, moving from a point called Quijata to Cuiyusuru, a distance of about a kilometer. A kind of fissure 5 cm wide and 30 cm deep opened as the dust column moved toward Cuiyusuru depositing a pale-gray dust. The column stopped near the oak tree she had left a short time before, and a hole 30 cm wide opened, and a smoke began to rise. Her first reaction was one of surprise and delight in watching the "pretty remolinito" as it traveled along, fissuring the soil.

Dolores Pulido, follows: About 4 p. m., after talking to my husband, I heard a kind of loud whistle, like the noise of water falling on live coals or hot embers. This noise was completely distinct from the underground noise I had been hearing, and the trees swayed strongly and continuously. I was about 100 m from the place where these things took place, when I saw, issuing from a crevice that had formed, a little cloud of gray and I smelled an odor like sulfur, and I noticed that some pines about 30 m from the orifice began to burn. I called to my husband. Then the ground rose in the form of a confused cake above the open fissure and then disappeared, but I cannot say whether it blew out or fell back-I believe it swallowed itself. I was sure the earth was on fire and it would consume itself. From the fissure arose a gray column of smoke, without force, depositing a fine gray dust.

On the afternoon of February 20, Dolores Pulido was working in the forest on Cerro de Jananboro. [S]he saw a column of smoke arising from Cuiyusuru; and since [s]he was part owner of land there, [s]he went to see what was taking place. [S]he reached the spot about 6 p. m. and saw smoke issuing from a hole in the ground. About this vent were low mounds of fine gray ash. [S]he was unable to approach closer than 8 m because of falling stones. [S]he then took fright and fled. [S]he returned to the place the next morning and found a gentle rain of "sand" falling about the spot.

FG3:
When I (Celedonio Gutierrez) visited a friend on a ranch called Titzicato, some few kilometers south of where the new volcano broke forth, he told me that some tremors had already begun, in these places and they heard many noises in the center of the earth. These tremors began to be felt in San Juan [Parangaricutiro] the following month, the 5th of February [1943], at midday, and every day until the 20th. During these 15 days of tremors there were some stronger than others; when we heard the subterranean noises we awaited the tremor. According to the noise the movement of the earth was strong or weak. They followed each other almost every minute. If they were delayed the noise or the tremor was stronger ….

The priest Sr. Jose Caballero, then parish priest of San Juan Parangaricutiro, related that light earth tremors began to be felt on February 7, 1943. On the 15th, at 5 p.m., they reached an alarming intensity. At 10 a.m. on the 20th subterranean noises were heard in San Juan Parangaricutiro; and the tremors were then, without exception, oscillatory. Sr. Caballero recalled that when he first came to San Juan Parangaricutiro and Paricutin as parish priest in 1933 the walls of the churches of both villages were fissured to a notable extent, suggesting to him that tremors were already active at that early date.

According to Professor Torres, tremors were again felt on the 5th of February 1943, but no importance was attached to them. By February 10 the tremors were more frequent and of greater intensity but were still considered to have a distant origin. On the 20th a messenger from San Juan Parangaricutiro arrived in Uruapan with word from the presidente, Sr. Felipe Cuara Amezcua, to the presidente of Uruapan, reporting in alarming terms that the region of San Juan Parangaricutiro and Paricutin was experiencing such strong and frequent tremors that neither the municipal nor church authorities, nor the people, knew what to do. On the same evening a second messenger arrived with word that the tremors had ceased but that a volcano had broken out between the fields of Cuiyusuru and Quitzocho. An urgent plea for help was then dispatched to the Governor of the State at Morelia. According to Sr. Felipe Cuara Amezcua, earth tremors began to be noticeable on February 5, 1943, increasing in number and intensity until more than 200 were experienced in a day. The tremors became so frequent and strong that it was feared that the church at San Juan Parangaricutiro, with its massive masonry walls, would collapse …. These tremors were accompanied by subterranean noises. Both the tremors and noises seemed to center in Cuiyusuru, which led him to believe that Cerro Prieto, an ancient cone which lay immediately adjacent to the farm, would break its agelong rest and erupt.

According to Robles Ramos (1943) the earthquakes varied between intensities 3 and 4, Mercalli's scale.

FG4:

As the helper was about to make the turn to commence a new furrow, a fissure split the earth in a direction toward Cerro de Canicjuata. The earth rose as a wall 10 m long and 2 m wide to a height of about a meter, and a gray smoke of a very fine gray dust ascended.

At 10 o'clock at night [20 February 1943] she [Aurora Cuara] could clearly see from San Juan Parangaricutiro, between the pine trees of the forest, incandescent bombs thrown into the air. Sometime between 11 and 12 p.m., the new volcano began to roar, incandescent stones were hurled up with great force, and a column of smoke, illuminated by lightning flashes, arose. The following day [21 February 1943], about 11 a.m., Sra. Cuara returned by the same path to see what had happened to her husband in San Nicolas. A small hill of stones of various sizes and of sand had formed about the vent where the smoke had first found exit. Some of the rocks hurled from the vent were very large and exploded in the air. She described the little hill as round in form, and she could clearly see a fire, which she afterwards learned was lava, issue slowly from the bottom of it.

… they went on horseback, riding rapidly, and arrived at the spot at about 6 p.m. [on 20 February 1943]. In the soil of Cuiyusuru they saw a sort of fissure, at the southwest end of which was a hole about a half a meter in diameter from which smoke issued and some hot rocks were hurled not very high in the air. Juan Anguiano Espinosa and Jesus Martinez, in order to obtain a nearer view, approached close to the hole. Solorio then saw a fracture forming about 6 m from the center of the vent and called to Espinosa and Martinez to come back. Hardly had they leapt back when the wall fell in, widening the orifice to 2 m and increasing the size of the smoke column.

In the afternoon (on 20 February 1943], when night began to fall, one could hear more noises. These we called rezaques.7 Some tongues of flame began to appear, as of fire, that rose about 800 m into the air, and others even higher that loosened a rain, as of artificial golden fire. At 8 or 9 at night, some flashes of lightning shot from the vent into the column of vapor. The column was now very dense and black and extended toward the south. It covered the grand mountain of Tancitaro, for the first sand and ashes were in this direction and cast the first cold shadow of the volcano over this area. From this hour the warming rays of the sun that warmed the mountains and the beautiful green fields ceased, and the green leaves of the trees and the smaller plants that nourished the cattle died from the ashes that now began to appear. How strange and rare to see the clouds form, the first clouds of the volcano. Only a short time before the sky was blue, for the dry season had already begun. So, then, we passed the first night, contemplating and admiring this new event. On the following day, Sunday the 21st, the dense vapors ceased. When the vapors diminished, the noise increased; and at 2 in the afternoon they were very strong. With each blast, white vapors accompanied by blue flames arose; the vapors appeared as if one shook a white sheet in the air.

After the first night, it threw up some tongues of fire, which were almost of pure sand. On the following night one noted that they were explosions of bombs and that the stones rose to a height of 500 m. They flew through the air to fall 300–400 m from the vent.

The first lava that the volcano gave forth, to the east of the little cone, flowed 3 m per hour, according to the data of Sr. Geologist don Ezequiel Ord6nez, who was sent by the Comisi6n lmpulsora y Coordinadora de Ia Investigacion Cientffica, Mexico, D. F., to observe this important novelty: This gentleman, 78 years of age, through his studies and experience, convinced us that there was no danger to our village and counseled that the people return to their homes. Now this same gentleman showed us the first lava flow, moving like dough, from which fell incandescent rocks from one side or another, such rocks as we knew before, without knowing how they formed.

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