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Bretón, M, Ibáñez, JM, León, Z et al. (2022) Historical and morphological evidence for multi-stage growth of El Volcancito, Volcán de Colima. *Journal of Volcanology and Geothermal Research*, 421. 107447. ISSN: 0377-0273

<https://doi.org/10.1016/j.jvolgeores.2021.107447>

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Historical and morphological evidence for multi-stage growth of El Volcancito, Volcán de Colima

1
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14 **Keywords:** Volcán de Colima, El Volcancito, flank eruption, historical volcanic evidence,
15 morphological reconstruction, magma-water interaction

16 17 **Abstract**

18 We present a multidisciplinary study of an important 1869 eruption of Volcán de Colima,
19 Mexico. This eruption created a parasitic cone, known as El Volcancito, which has traditionally
20 been attributed to a small flank eruption. However, new analysis of historical records suggests
21 that the size, explosivity, and duration of this eruption have been seriously underestimated.

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22 While previous reports suggest that activity ceased after ~3 years, our evidence shows that the
23 eruption was highly energetic and constituted multiple eruptive phases over an 8-year period.
24 There was a substantial emission of volcanic material into the atmosphere and the event directly
25 affected communities up to 150 km from the volcano. A new estimate of the volume of material
26 emitted (0.8 km^3) is almost four times higher than the previous estimate (0.21 km^3), and
27 represents the largest historical andesite lava deposit at Volcán de Colima. At least 10 large
28 explosions with eruptive columns of $> 6 \text{ km}$ occurred. The eruption differed significantly to
29 activity from the central summit cone in terms of eruption dynamics, evolution of activity over
30 time, and petrology; as such, it cannot be explained using the widely accepted eruptive scheme
31 for this volcano. Based on seismic and petrological evidence, we suggest that the highly
32 energetic behavior can be explained by changes in the local stress field following two large
33 regional earthquakes ($M > 8.0$) and subsequent magma-groundwater interaction. This study
34 challenges the common assumption that most monogenetic cone-building flank eruptions at
35 andesitic volcanoes are low energy compared with edifice-building summit activity, which has
36 important implications for risk analysis at similar volcanoes worldwide.

37

38 **1 Introduction**

39 Volcanic complexes form dynamically as the consequence of multiple geodynamic
40 processes and different magmatic sources; no volcano has one single eruptive process, style of
41 eruption, or magma type. Not even the location of the eruptive center is fixed; there is significant
42 spatial mobility in the construction and destruction of volcanic features, which is ultimately
43 reflected in the volcano morphology. Composite or stratovolcanoes are classically described as
44 having a particular volcanic structure and activity type (i.e., summit eruptions interspersed with

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45 periods of quiescence). However, the historical and geological records of many active
46 stratovolcanoes reveal more complex eruptive evolution (e.g., Biggs et al., 2016). Rivalta et al.
47 (2019) suggested that while most stratovolcano eruptions take place in the summit area, the
48 chance of eruptive activity from other locations (e.g., lateral fissures and parasitic cones on the
49 flanks of the volcano) cannot be discounted. This uncertainty has serious implications for
50 volcanic hazard assessment.

51 From the perspective of eruption dynamics, new flank or parasite basaltic–andesitic
52 volcanic cones are usually characterized by moderate, Strombolian-type explosive activity, or by
53 the effusion of lava (e.g., Smith and Nemeth, 2017). Often, the end result is the construction of
54 monogenetic cinder cones (e.g., De la Cruz Reina and Yokohama, 2011; Németh and Kereszturi,
55 2015), although on occasion the new eruptive locus can mark a true migration of the emission
56 center (e.g., Macdonald and Abbott, 1983). Such shifts were observed at the Asama and Usu
57 volcanoes in Japan (Tomiya and Takahashi, 2005; Aoki et al., 2013; Prudencio et al., 2017).
58 There are many examples of new cones significantly modifying morphology and/or eruptive
59 dynamics, including those at Mt. Etna, Italy (Behncke et al., 2014; Cappello et al., 2019), one of
60 the most intensively studied and monitored volcanoes in the world. In addition to eruption
61 locations, one of the great challenges of modern volcanology is to understand the causes of the
62 transition from effusive to explosive dynamics and vice versa. For silicic magmas, Cassidy et al.
63 (2018) and Wadsworth et al. (2020) highlighted the importance of water over the magma
64 reservoir, while Allison et al. (2021) pointed to CO₂ exsolution as the main driver of large
65 explosive basaltic eruptions.

66 The occurrence of parasitic cones or flank eruptions on stratovolcanoes is a topic of
67 interest for the scientific community. Acocella and Neri (2003) reviewed some examples and

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68 presented a model explaining their occurrence; in particular, they highlighted how the stress
69 field, which is controlled by regional tectonics (including tectonic earthquakes), is one of the
70 most invoked mechanisms to explain this type of eruption. In their analysis of Mt. Etna volcano
71 they consider that the influence of regional stress and structures as the most likely controller of
72 magma ascent. Sharp et al. (1981) analyzed historical flank eruptions of Mt Etna and suggested
73 that large local and regional earthquakes are one of the mechanisms triggering these eruptions
74 (along with pressure changes in the magma chamber); they suggest that such earthquakes can
75 induce fracturing in the edifice, which owing to tensile forces favors the occurrence of flank
76 eruptions. In contrast, in their study of Teide volcano and its lateral eruptions, Martí and Geyer
77 (2009) suggest that the geometry and number of potential magma chambers and other lateral
78 reservoirs feeding the central volcano are the most important factors controlling the stress field,
79 and therefore the occurrence of flank eruptions. Yokoyama (2015) presented a classification
80 system for parasitic cones and flank eruptions based on spatial distribution and possible
81 triggering mechanisms.

82 However, within the volcanological community, there is an open question related to the
83 possibility of earthquake-volcano interactions. References to earthquake-volcano interactions can
84 be found in ancient oral traditions from around the globe. Troll et al. (2015) highlighted ancient
85 oral traditions used to describe volcano-earthquake interactions at Merapi volcano. Ancient
86 Greek communities also hypothesized the relationship between earthquakes and volcanoes (e.g.,
87 Vilagran, 2013). The Greek geographer and historian Strabo (63 BC–AD 19) records an
88 Aristotelian hypothesis that relates earthquakes and volcanoes through "humid and warm winds
89 that ran through the cavities of the Earth ", where "volcanic activity implies an intense
90 circulation of gas currents in the subsoil fueled by Aristotelian underground fires that explode in

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91 the form of eruptions and earthquakes”. Darwin (1840) was the first modern observer to suggest
92 a link, after observing a correlation between a large 1835 earthquake in Chile and several
93 volcanic eruptions along the Andean cordillera. However, Watt et al. (2009) discussed the
94 possibility that Darwin's report was biased by heightened awareness, since much of Darwin's
95 record is based on secondary sources.

96 Since then, numerous studies have considered the link between volcanic eruptions and the
97 occurrence of large tectonic earthquakes (e.g., Yokoyama, 1971; Nakamura, 1975; Zobin and
98 Levina, 1998; Hill et al., 2002; Marzocchi et al., 2002, 2004; Manga and Brodsky, 2006; Walter
99 and Amelung, 2007; Eggert and Walter, 2009; De la Cruz-Reyna et al., 2010). Linde and Sacks
100 (1998) suggested that volcanic eruptions are generally triggered within days of the main shock;
101 however, Sawi and Manga (2018) showed that the triggering of eruptions within 5 days of an
102 earthquake only occurs for eruptions before 1900, for which eruption records are incomplete.
103 This likely reflects reporting bias, with people more likely to report eruptions shortly after
104 earthquakes owing to heightened awareness. Based on modern and more complete eruption
105 records, numerous studies have shown that longer-term triggering over months to years is more
106 common (Marzocchi, 2002; Nishimura, 2017; Sawi and Manga 2018; Jenkins et al., 2021).

107 The Mw 9.5 Chile earthquake of 22 May 1960 is thought to have triggered volcanic
108 eruptions for at least 7–10 years, with some of this activity occurring > 600 km away from the
109 epicenter (Watt et al., 2009). However, for these long time intervals, Marzocchi (2002) suggested
110 that the possibility of seismically-triggered eruptions be treated with caution owing to the small
111 sample size. Sawi and Manga (2018) expanded the definition of a triggered eruption to include
112 the possibility of $M > 6$ or greater earthquakes within 5 days and 800 km of explosive eruptions.

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113 In general, statistical correlation is the only quantitative way to relate large earthquakes to
114 volcanic eruptions (e.g., Jenkins et al., 2021). From statistical analysis of volcanoes located
115 within 200 km of large earthquakes (magnitude 7.5) or greater, Nishimura (2017) observed that
116 eruption occurrence probability increases by approximately 50% for 5 years after the earthquake.
117 However, the triggering of volcanic eruptions is a complex phenomenon involving multiple local
118 effects, including quasi static or metastable volcanic processes (i.e., the critical state). For this
119 reason, different volcanic systems will respond differently to seismic activity, and thus, statistical
120 analysis may not always be the best technique for identifying relationships.

121 Today, detailed volcanic hazard and risk plans have been developed for most relevant
122 volcanoes. These plans include numerical models of lava flows, ash-fall, volcanic collapses,
123 lahars, and pyroclastic flows, and in theory, offer insight into all possible eruption scenarios and
124 consequences. However, new eruptive processes can invalidate established models; for example,
125 models that predict the geometry of lava flow fields or changes in the style and frequency of
126 eruptions may no longer be applicable (e.g., Watt, 2019). Moreover, there remains significant
127 uncertainty with respect to the potential locations of new eruptive centers. Without insight into
128 possible eruptive locations, magma rheology, or changes in the morphology of the volcano, we
129 cannot predict future eruptive dynamics or the types of volcanic products. In a worst-case
130 scenario, changes in eruptive behavior could lead to more dangerous styles of activity, with
131 hazard and risk implications on local, regional, or even global scales.

132 El Volcancito, a prominent andesite parasitic cone on the flanks of Volcán de Colima,
133 represents the only flank or parasitic eruption within the recent history (last 500 years) of Colima
134 volcano and forms a volcanic structure of considerable dimensions. However, unlike traditional
135 cinder cones, El Volcancito contains a dome similar to those at the summit of Volcán de Colima.

136 Contemporary historical narratives describe a high-energy process, with frequent explosions,
137 emissions of lava, rapid growth of the volcanic structure, and multiple intervals of destructive
138 and constructive activity. Even the name "El Volcancito" ("the small volcano") records the
139 unique and impressive nature of the eruption, which attracted scientific interest at that time.
140 However, successive sub-Plinian eruptions from Colima's central cone during the 20th century
141 diverted the attention of the scientific community, which has largely forgotten the fascinating
142 eruption of El Volcancito. In this study, we combined new analyses of historical records,
143 reconstructed three-dimensional (3D) morphology (from new drone-captured imagery), and data
144 from published seismic and petrological studies to re-evaluate the formation of El Volcancito.
145 Our estimate of the eruptive volume (0.8 km^3) far exceeds an early topographic estimate (0.21
146 km^3), which remained accepted until now. Moreover, published studies all report an end date of
147 1872, but our analyses show that the eruption continued for 8 years, until 1877. In our model, we
148 suggest that the eruption can be explained by a combination of factors, including the influence of
149 large regional tectonic earthquakes that resulted in stress conditions conducive to magma ascent
150 and depressurization, and the interaction of magma with shallow groundwater. Our hypothesis
151 has serious implications for hazard models at Colima, and offers a new vision of flank
152 monogenetic cone development that has relevance to many (andesitic) volcanoes around the
153 world.

154 **2 Tectonic and geological background**

155 **2.1 Geological and volcanological framework**

156 Volcán de Colima, situated within the Trans-Mexican Volcanic Belt (Figure 1), is one of
157 the most active volcanoes in North America (Savov et al., 2008; Crummy et al., 2019a) and has
158 been widely studied from geological, geodynamic, and morphological perspectives (e.g., Norini

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159 et al., 2019). The Trans-Mexican Volcanic Belt (TMVB), a 1000-km-long Neogene continental
160 arc showing large variations in magma composition and volcanic style, runs along southern edge
161 of the North America plate, which overrides the subducting Rivera microplate and northern
162 Cocos plate (Ferrari et al., 2012; Gómez-Alvarez et al., 2021). The Colima Volcanic Complex
163 (Figure 1) is made up of two main units: the currently active Fuego de Colima, with a height of
164 3,860 m above sea level (m a.s.l.), and the older Nevado de Colima (4,330 m a.s.l.). The Colima
165 graben, which is 90 km long and 20–60 km wide, represents a N–S rift of the E–W trending
166 Mexican Volcanic Belt (Allan and Carmichael, 1984). Over the last 1.7 Ma, volcanism in the
167 Colima graben has evolved from biotite-to-phlogopite-to-amphibole-containing dacitic–andesitic
168 eruptions. Since the Early Pliocene, the Colima graben has served as a locus for the eruption of
169 alkaline lavas, the most recent of which are basanites and minettes erupted from Late Pleistocene
170 cinder cones (Luhr and Carmichael, 1980). At the same time, the locus of magmatic activity
171 moved from El Cantaro volcano (to the north) towards Nevado De Colima and the underlying
172 Paleofuego de Colima (active approximately 8,100 years ago; Robin et al., 1990), and finally to
173 the modern Volcán de Fuego de Colima stratovolcano (hereafter, Volcán de Colima; Luhr and
174 Carmichael, 1980, 1990a). The eruptive history of Volcán de Colima, through Paleofuego and
175 Nevado de Colima to the present day, includes different eruptive dynamics that have been
176 described in detail elsewhere (Robin et al., 1987, 1990, 1991).

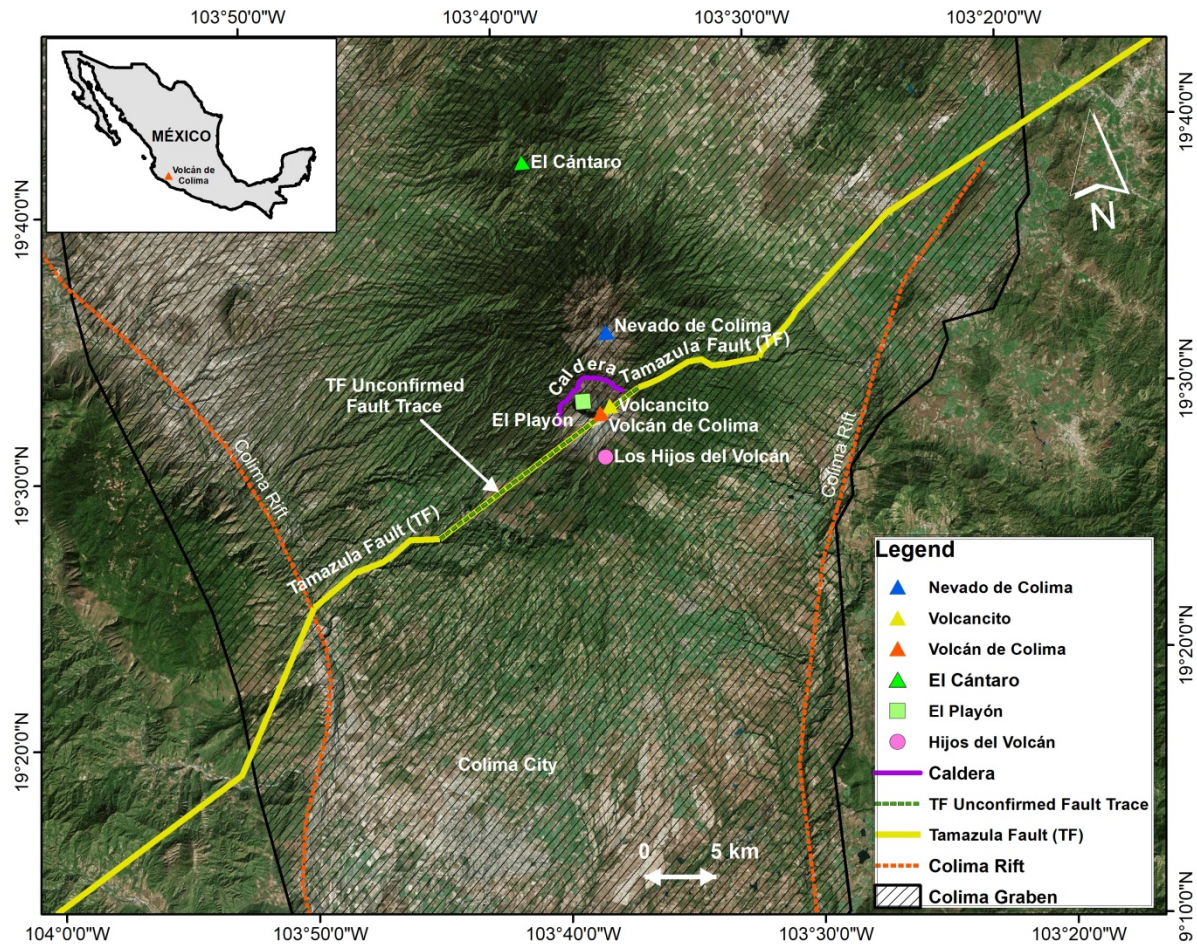
177 Of significance in terms of evolution and risk is a voluminous debris avalanche deposit of
178 22–33 km³, (Stoopes and Sheridan, 1992; Capra and Macias, 2002), which originated from a
179 lateral collapse and extends to the Pacific coast, 70 km away (Robin et al., 1987; Stoopes and
180 Sheridan, 1992). Over the past 500 years, Colima has had more than 40 significant eruptive

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181 events (Bretón et al., 2002), the most recent of which occurred in 2013, 2015, and 2017. The
182 activity manifests in various forms, many of which are highly explosive.

183 Paleofuego may have had an elevation of $> 4,100$ m before collapsing to form a lateral
184 horseshoe-shaped depression within which the Volcán de Colima active cone grew. The age of
185 this collapse is not well defined, with estimates ranging from 4,300 to 9,400 years (Robin et al.,
186 1987; Luhr and Prestegard, 1988), to tens of thousands of years (Komorowski et al., 1997;
187 Cortés et al., 2010; Roverato et al., 2011). A critical morphological feature of the Volcán de
188 Colima edifice is a vertical escarpment known as the Calderic wall of El Playón, which is
189 interpreted as resulting from at least nine lateral collapse events over the last 45,000 years
190 (Komorowski et al., 1997). The Volcán de Colima edifice has slopes of between 36° and 40° and
191 hosts a number of important lateral cones, including El Volcancito (3680 m a.s.l.) and Los Hijos
192 (2720 m a.s.l.). In addition, there are many smaller monogenetic cones (120–300 m above their
193 base) with slopes of 30° – 35° (Lugo Hubp et al., 1993; Cortés et al., 2005). In summary, the
194 morphology of Volcán de Colima reflects multiple constructive and destructive episodes (Cortés
195 et al., 2010, 2019; Roverato et al., 2011, 2019).

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196
197 **Figure 1.** Satellite image of Volcán de Colima showing the major volcanic structures. The
198 yellow line marks the accepted trace of the Tamazula Fault (TF), and green dashed line
199 represents the unconfirmed fault trace. Dashed orange lines mark the boundaries of the Colima
200 Rift.
201

202 Historical records extend back just 500 years (Bretón et al., 2002; Bretón, 2012); although,
203 Crummy et al. (2014, 2019a,b) analyzed older eruptions from a petrological point of view.
204 However, there remains a lack of data for robust eruption frequency modelling. Historical
205 eruptions of Volcán de Colima have tended to be moderate in size (Volcanic Explosivity Index,
206 or VEI, of < 3), with events in 1818 and 1913 marking the largest recent eruptive episodes. The
207 explosive eruption of 15 February 1818 could be heard several tens of kilometers from the
208 volcano and the ash column travelled a significant distance. Based on historical and

209 volcanological descriptions, the 1818 eruption has been classified as sub-Plinian and assigned as
210 a VEI 4 event (Luhr and Carmichael, 1990a,b).

211 **2.2 Tectono-seismic controls on activity**

212 The development of the Colima Volcanic Complex has been controlled by the action of
213 two active, nearly orthogonal, faults systems. The first is associated with the opening of the
214 Colima rift, a N–S striking extensional sedimentary basin containing ~3000 m of sedimentary
215 strata that underlie the volcanic complex; the other is associated with the regional Tamazula
216 Fault (Figure 1; Norini et al., 2019). The Tamazula Fault is a regional basement structure that
217 extends > 160 km in a NE–SW direction and passes directly through the Colima Volcanic
218 Complex (e.g., Garduño et al., 1998; Zobin et al., 2002). Pacheco et al. (2003) related the
219 occurrence of large regional earthquakes ($M_w > 7.0$) in the Colima Volcanic Complex and
220 Manzanillo areas to the reactivation of crustal structures directly on or parallel to the Tamazula
221 Fault. The Fault was an important factor in gravity collapses of old volcanic structures, while the
222 orientation of El Volcancito and other domes also suggest a link. This evidence implies that the
223 Tamazula Fault has played a fundamental role in facilitating magma ascent at Colima (Garduño,
224 1998).

225 The Tamazula fault is complex, and cannot be simplified by a constant strike or dip.
226 Pacheco et al. (2003) showed that the most recently active segment dips 50° – 55° to the
227 northwest, has a strike ~SW–NE, and reaches 20 km depth; the associated extensional stress field
228 is oriented NW–SE. The southernmost segment of the fault, located between Volcán de Colima
229 and the Pacific coast, extends > 40 km. Geological and structural maps (Garduño et al., 1998)
230 suggest that the strike of the Tamazula Fault changes beneath the Colima Volcanic Complex
231 (Figure 1), and more specifically, intersects the location of the El Volcancito cone. Owing to

232 increased energy exchange, we can assume that this structural change has resulted in additional
233 localized brittle behavior. Based on seismic velocity and attenuation, Sychev et al. (2019)
234 presented a 3D tomographic model of magma ascent at Colima, from the upper mantle to the
235 surface. They identified the Tamazula Fault as the most important structural element controlling
236 the morphology of magma ascent. Moreover, they also identified a shallow magma storage
237 structure 5–12 km beneath the volcano. They suggest that magma in this storage region is
238 supersaturated with fluid and undergoes gradual fractionation, which is consistent with the high
239 explosivity of eruptions at Volcán de Colima.

240 **2.3 Petrological perspective**

241 The overall timing and compositions of Holocene activity at Colima have been
242 reconstructed over decades of fieldwork and sampling (Luhr and Carmichael, 1980, 1990a,b;
243 Luhr, 2002; Savov et al., 2008; Luhr et al., 2010; Crummy et al., 2019a,b). Currently erupting
244 rocks are calc-alkaline andesites ($\text{SiO}_2 = 56\text{--}61.5$ wt.%; Savov et al., 2008) with two-pyroxene
245 and plagioclase-groundmass eruption temperature estimates of $960^\circ\text{C}\text{--}1020^\circ\text{C}$ (Savov et al.,
246 2008); H_2O contents (based on the chemistry of plagioclase rims, groundmass glasses, and melt
247 inclusions) range from ~ 1.5 wt.%, for degassed mostly dome forming andesite magmas, to ~ 3.6
248 wt.% for pumice/scoria samples (Atlas et al., 2006; Savov et al., 2008 and references therein;
249 Connor et al., 2019). Based on mineral equilibria and melt inclusion entrapment pressures, the
250 depth of H_2O saturation under Volcán de Colima is estimated to be ~ 6.5 km (Reubi et al., 2019).
251 The phenocrysts of deep-sourced magmas (such as those from the 1913 eruption; Luhr, 2002,
252 Savov et al., 2008) include plagioclase (An 45%–60%), clinopyroxene (Mg# 70–76), amphibole
253 without reaction rims, and accessory (partially resorbed) olivine. Shallower and more evolved
254 magma types contain resorbed rimmed amphibole and more abundant orthopyroxene and

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255 accessory Fe-Ti oxides (Luhr and Carmichael, 1980, 1990; Savov et al., 2008; Crummy et al.,
256 2014; Ruebi et al., 2013, 2019). The majority of magmas have porphyritic textures with a total
257 phenocryst range of 30%–52% (minimum and maximum for the 1913 and 1961 magmas,
258 respectively; Luhr and Carmichael, 1980; Luhr et al., 2010).

259 Based on tephrochronology, Luhr (2002) proposed that Holocene activity can be divided
260 into five-stage cycles, within which Stage 5 represents VEI > 4 Plinian eruptions with recurrence
261 intervals of ~100 years; the last two such eruptions took place in 1818 and 1913 (Luhr, 2002;
262 Connor et al., 2019). Other stages include an open crater, ascending lava dome, dome filling he
263 crater and plugging the conduit, and intermittent-minor-major eruptions. The progression of
264 stages explains the entire accepted timeline for magma storage, evolution, and subsequent
265 emplacement of Volcán de Colima andesites (Luhr, 2002). However, the 1869 activity at El
266 Volcancito was unique, containing assorted eruption styles (or “stages”) over a matter of only
267 several months.

268 Conventional models for Volcán de Colima postulate that most magmas arrive at the
269 volcano conduit as highly crystalline and degassed (via slow ascent rates) high silica andesites
270 that form volcanic domes and lava flows similar to the 1961–62, 1975–76, 1981, 1991, 1998–
271 2008, and 2009–17 volcanic pulses. More explosive eruptions appear to be driven by injections
272 of hotter, more mafic, and rapidly ascending (and therefore volatile rich) melt batches (Luhr and
273 Carmichael, 1980; Savov et al., 2008). Degassed magmas are overtaken by gas rich “slugs”
274 derived from the mafic magmas, which apply excessive pressure on pre-existing volcanic domes,
275 resulting in large explosions (Luhr, 2002; Savov et al., 2008; Reyes-Dávila et al., 2016). Based
276 on ^{210}Pb – ^{226}Ra disequilibrium, Ruebi et al. (2013) demonstrated that shifts from effusive to
277 explosive Vulcanian eruptive phases at Colima are not related to changes in degassing mode,

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278 which is only relevant for large explosive eruptions in which hydrous magmas did not have
279 sufficient time to degas (e.g., those seen from the summit of Colima).

280 The El Volcancito dome samples differ from the deposits of the 1818 and 1913 eruptions,
281 which were more mafic (a few percent more olivine in the pumice), volatile rich, and Plinian to
282 sub-Plinian in nature. Unlike the 1818 and 1913 deposits (Savov et al., 2008; Luhr et al., 2010),
283 the textures of the El Volcancito magmas lack evidence for volatile additions via mingling and
284 mixing with rapidly ascending mafic melts. In 1818 and 1913, hornblende crystals lacked
285 reaction rims, meaning that they were in equilibrium with volatile (H₂O)-saturated magmas
286 (specifically, at least 4 wt.% H₂O; e.g., Rutherford and Hill, 1993). Regrettably, scoria samples
287 with proven 1869 ages have not been preserved (buried under 1913 pyroclastic density currents)
288 and so direct comparisons with other scoria samples with known physico-chemical conditions of
289 formation (e.g., those from 1913 and 1818) are not possible. Moreover, there are no SO₂ or other
290 gas flux measurements to confirm the presence of mafic magma batches involved in the initial
291 stages of the 1869 El Volcancito eruption (Savov et al., 2008).

292 In contrast, except for slight enrichment in hornblende crystals (up to 3.5%; Luhr and
293 Carmichael, 1980), the deep magmatic signatures (major element compositions, crystal cargo,
294 etc.) of the El Volcancito dome material match those of the modern summit domes, all of which
295 formed from volatile-poor andesites. However, they differ in terms of elevated concentrations of
296 fluid mobile elements (Zn, Rb, Sr, Cs, Ba, Ce, Pb, and U) in El Volcancito dome samples (Savov
297 et al., 2008), which may be explained by additions of (external) fluid-rich sources. In fact, the
298 1869 magmas have the highest Ba (incl. Ba/La ratios) and Rb concentrations of any Volcán de
299 Colima andesites, including those erupted in the VEI 4 events of 1818 and 1913 (Savov et al.,
300 2008). Highly explosive activity at Colima from 2004 to 2005 was linked to magma-water

301 interaction at an aquifer (Palo et al., 2009). Similarly, in addition to the high Ba and Rb contents
302 of the 1869 magmas, slight depletions of Eu and Dy (relatively fluid immobile elements) may
303 signify some degree of interaction with lithologies containing amphiboles, zeolites, and clays,
304 which occur in the wall rocks of H₂O-rich reservoirs.

305 In summary, the El Volcancito eruption offers a contradiction. It was petrologically distinct
306 from the 1913 and 1818 eruptions, but shared some of their explosivity. In contrast, it was
307 petrologically similar to summit dome eruptions, but dynamically much more vigorous. The El
308 Volcancito explosiveness was not driven by exsolution of magmatic volatiles from slowly
309 evolving magma batches in a closed conduit-sill system (there is no evidence for H₂O saturation
310 such as unreacted hornblendes and micro-vesiculation; Connor et al., 2019). The unique trace
311 element signature (but major element composition indistinguishable from other domes) suggest
312 that there must have been an external addition of excess fluids and/or assimilation of
313 hydrothermally altered wall rock immediately prior to eruption; this would have impacted the
314 eruption style without changing the mineralogy or major element composition of the magma.

315 **3 Materials and methods**

316 **3.1 Historical records**

317 We analysed historical materials including written, pictorial, and photographic sources
318 available in different archives. Most of these materials are not accessible online, and were
319 obtained through visits to libraries, archives, newspapers, art galleries, museums, and private
320 collections.

321 Resources from private collections include those of Manuel Gómez Z., who took
322 photographs, notes, and drawings related to the growth of El Volcancito from 1869 to 1885;
323 many of these works were privately sold in the city of Colima. In addition, Jesús Martínez

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324 produced paintings of the main eruptions of 1872 and 1873, later distributed to different owners
325 in Colima and Jalisco states. The drawings of Francisco Rivas, based in Tonila (Jalisco),
326 captured the main explosions from 1869 to 1872. These drawings were lithographically
327 reproduced in Colima and sold in both Colima and Jalisco states. In August 1869, Miguel N.
328 Orozco made an ascent of the volcano and detailed aspects of the volcanic activity and the
329 growth of the cone. He was accompanied by Manuel Gómez Z. and Jesús Martínez, who took
330 photographs, notes, and paintings.

331 Written accounts by residents of the area include descriptions of the activity and images of
332 the ash clouds and explosions. Many of these impressions were sent in the form of letters to
333 Mariano Bárcena, who collected them in his writings, referenced as Bárcena (1887a,b). Other
334 descriptions and drawings remained as private documents held within families. Many families
335 have bequeathed these documents or allowed researchers at the University of Colima to make
336 copies. For this reason, we present many unpublished documents that have now become part of
337 the historical archive of the Volcanological Observatory of the University of Colima. Many of
338 the reports incorporated in this manuscript (those with literal translations) correspond to these
339 unpublished documents.

340 Other stories and observations were collected by Father José María Arreola in the
341 magazine of the Antonio Alzate Scientific Society, referenced as Arreola (1915). These include
342 active and credible observers (based on their economic and social position), including Josefa
343 Parra (1869 to 1872) from Zapotlán (Jalisco), and Cesáreo Montenegro. Some of their
344 observations were also published in local newspapers for which archives are available.

345 We visited a number of public institutions to obtain information, including the Historical
346 Archive of the Municipality of Colima (AHMC); the Graphic Art Collection of Munich,

347 Germany to obtain paintings of Rugendas (reissued by the Banamex Cultural Development
348 Collection and Colima University in 1997); the Historical Archive of the Archbishopric of
349 Zapotlán, Jalisco; and the National Photo Library of Mexico. Additional information was
350 collated from the library of the Smithsonian and the Library of Congress in Washington DC.

351 Finally, we consulted documents, newspapers, bulletins, brochures, and legal documents
352 from the Bulletin of the Statistical Geographical National Institute of the Mexican Republic;
353 different printed editions of El Renacimiento, a newspaper edited in 1866, which can be
354 consulted at the National Hemeroteca of Mexico where the chronicles of Dolfus and Montserrat
355 were edited; and the Official Gazette of the State of Colima.

356 Appendix A contains the original Spanish text of the English translations presented in this
357 manuscript.

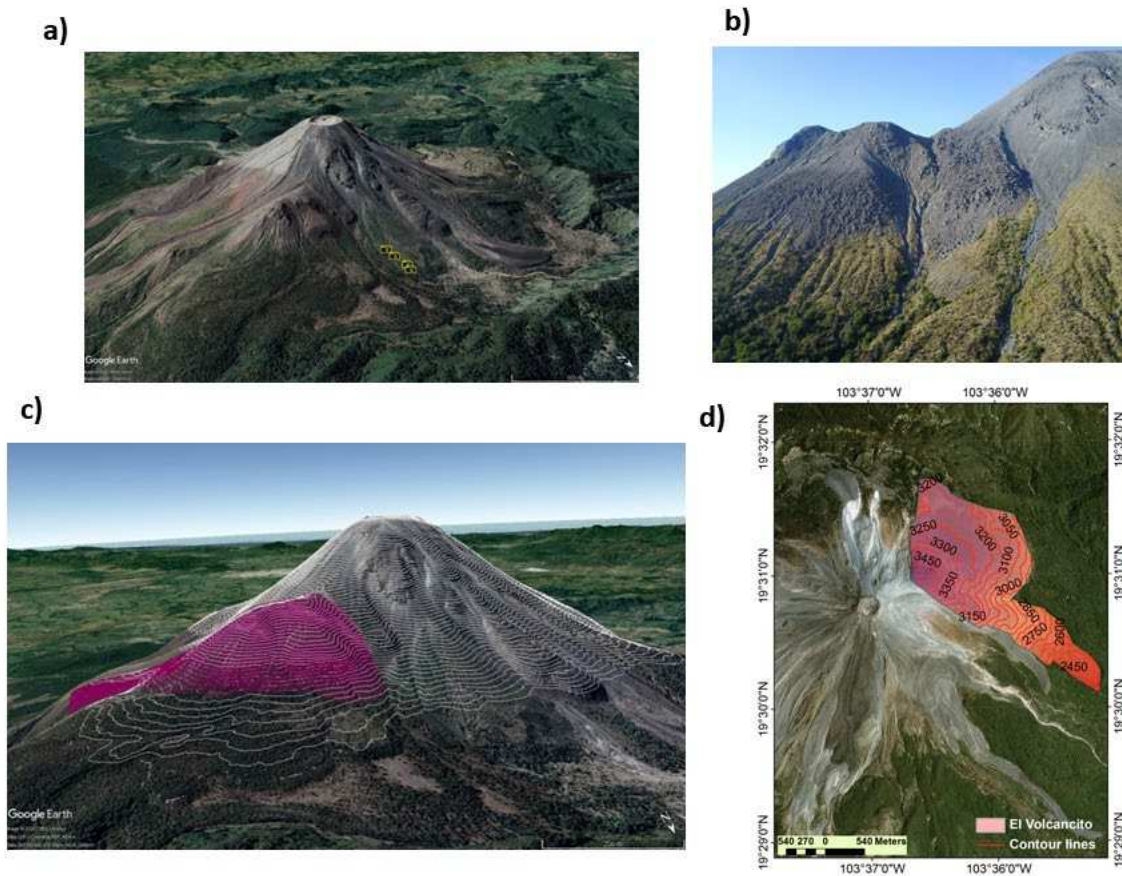
358 **3.2 Volume estimation**

359 To create a 3D model of El Volcancito and estimate the eruptive volume, we created a 5-m
360 digital elevation model (DEM) from aerial images captured by a drone on 22 May 2019 (Figure
361 2a,b). The photographs were taken at an average elevation of 3408.18 m, based on Global
362 Positioning System (GPS) data from the drone. Using the ArcGis software, we generated a set of
363 contour lines of the DEM (Figure 2c) and digitally traced polygons using lines spaced every 50
364 m. With this method, we obtained 14 prismoids with elevations ranging between 2250 to 3561 m
365 a.s.l. (Figure 2d) that define the surface of each contour curve to obtain the areas of each cross
366 section.

367 Once the DEM was determined with 50-m contour lines delineated, we calculated the
368 volume of El Volcancito. For quality control and to verify the results, we chose to compare two
369 different methods: the “prismoid” method and a routine developed in Matlab© named

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370 “Conv hull”. Although the Conv hull estimation is more accurate (because it uses a larger data
371 set), the prismoid method is considered a standard procedure to calculate the volume of earth
372 masses and is used by land surveyors and engineers (Lewinska and Galas, 2021). The Conv hull
373 function can approximate the volume of irregular polygons from 2D and 3D point sets, and is
374 usually applied to geometrical studies and volume estimations (Carrea, et al., 2021).



375

376 **Figure 2.** El Volcancito and the locations of drone photographs. (a) Google Earth image of
377 Volcán de Colima showing the locations of drone images taken on 22 May 2019. (b) Photograph
378 of El Volcancito, taken with the drone on 22 May 2019 at an elevation of 3421.784 m from a
379 position with the coordinates 103°36'42.63”W and 19°31'26.51”N. (c) Three-dimensional view
380 of Volcán de Colima (white) and El Volcancito (purple) with the 50-m contour lines delineated
381 (image from Google Earth 2020). (d) Satellite image of the Colima Volcanic Complex, with the
382 El Volcancito cone highlighted and labelled using 50-m contour lines.

383

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384 A prismoid is defined as a solid that has two flat and parallel faces of regular or irregular
385 shape, joined by flat or warped surfaces, in which parallel lines can be drawn between the faces.
386 To apply the prismoid formula to the 14 prismoids with $d = 100$ m, the areas of the midsection
387 (A_m) and extreme areas were calculated using Eq. 1:

$$388 \quad V = \frac{d}{6} (A_1 + 4A_m + A_2) \quad (1)$$

389 where A_1 and A_2 are the extreme areas, A_m is the area of the cross section at the midpoint, and d
390 is the distance between the extreme cross sections A_1 and A_2 .

391 In the second procedure, the “convhull” function can approximate the volume of irregular
392 polygons from 2D and 3D point sets. To use the data from the El Volcancito DEM in Matlab®,
393 the DEM and its cross-sections were exported as points. For the volume computation of the full
394 3D point cloud, we considered the natural geometric complexities encountered for rock fall
395 source shapes (convex or concave). We then calculated cross section volumes at 100 m intervals
396 and took the sum of these cross sections as the total volume of eruptive material during the
397 formation of El Volcancito.

398 It is important to note that the calculated eruptive volume is an underestimate of the true
399 eruptive volume because we were unable to include the volume of ash owing to a lack of data.
400 While there were contemporary reports of ashfall > 170 km from the volcano, the thickness of
401 the deposited ash was not recorded. As such, the volume of material emitted into the atmosphere
402 is unquantifiable.

403 **4 Results**

404 **4.1 Eruptive sequence**

405 4.1.1 Pre-eruptive period

406 Two large regional earthquakes occurred in the decades before the El Volcancito
407 eruption—those in 1845 and 1858—and may have had structural consequences for the volcano.
408 Contemporary reports suggest that the largest of the two, that in 1845, caused landslides on the
409 flanks of the volcano. Following a widely felt earthquake on 10 April 1845 (note, some authors
410 place the date on 7 April; e.g., de Villar, 2004), historical sources report a prominent scar on the
411 volcano flank (Bretón et al., 2002. Moreover, one report describes how “[...] *in Colima and*
412 *adjacent towns an extraordinary noise was noticed in those days, as of great masses that emerge*
413 *from the interior of the earth and fall into a great lake of water of great depth*” (literal
414 translation). Lomnitz (1999) estimated a magnitude of at least 8.0 M for this event, and
415 suggested that the epicenter was in Guerrero state. Damage attributed to the event was reported
416 across Mexico, and in the Colima area it exceeded that of the 1985 earthquake (e.g., Eissler et
417 al., 1986; Aguilar et al., 1989; del Villar, 2004), which had a magnitude of 8.1 Mw. The
418 epicenter of the 1985 earthquake was along the Michoacán coast, closer to Colima than that of
419 the 1845 Guerrero event. Given changes in construction styles between 1845 and 1985, structural
420 damages are not by themselves indicative of relative earthquake magnitudes; however, the
421 effects on the volcanic edifice can be compared. The 1845 earthquake produced evident damage,
422 while the 1985 earthquake did not, which suggests that the magnitude and/or distance between
423 the epicenter of the 1845 event and Volcán de Colima have been underestimated.

424 The earthquake of 19 June 1858 was also felt across Mexico. It had an estimated
425 magnitude of 8.0 (del Villar, 2004), and the epicenter was likely along the Michoacán coast, less
426 than 400 km from Colima, with the area of impact similar to that of the 1985 event.

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427 In March 1866, a French expedition under geologists Auguste Dollfus and Eugène de
428 Montserrat reported 21 gas vents on the northwest side of the summit crater of Volcán de Colima
429 (Dollfus and Montserrat, 1869a,b) that had appeared a few years after the 1858 earthquake.
430 Some were located at the location where El Volcancito would appear 3 years later. The vents had
431 temperatures of 76°C–80°C, and most were emitting water vapor, with little evidence for sulfuric
432 acid¹. They also describe the crater as “a funnel or bucket”, reaching 125–250 m depth (Dollfus
433 and Montserrat, 1869a,b; Bárcena, 1887a,b; Ortoll, 1988). This description differs from that of
434 the jagged appearance reported after the explosive summit eruption of 1818. Together with
435 differences in the crater dimensions (i.e., diameter and depth) given by this expedition and those
436 reported 32 years earlier (Harkort et al., 1849), this suggests morphological changes owing to
437 continued volcanic activity; however, supporting evidence for explosive activity is not found in
438 the volcanological records. Owing to the intense summit fumarolic activity discovered by the
439 French expedition, it is credible to assume they originated some time before 1866. On the other
440 hand, the low temperature of the fumaroles and what appears to be low sulfur emissions are
441 compatible with a magmatic source sealed by the presence of deep aquifers, as observed at other
442 volcanoes (e.g., Caselli et al., 2004, 2007; Goyanes et al., 2014).

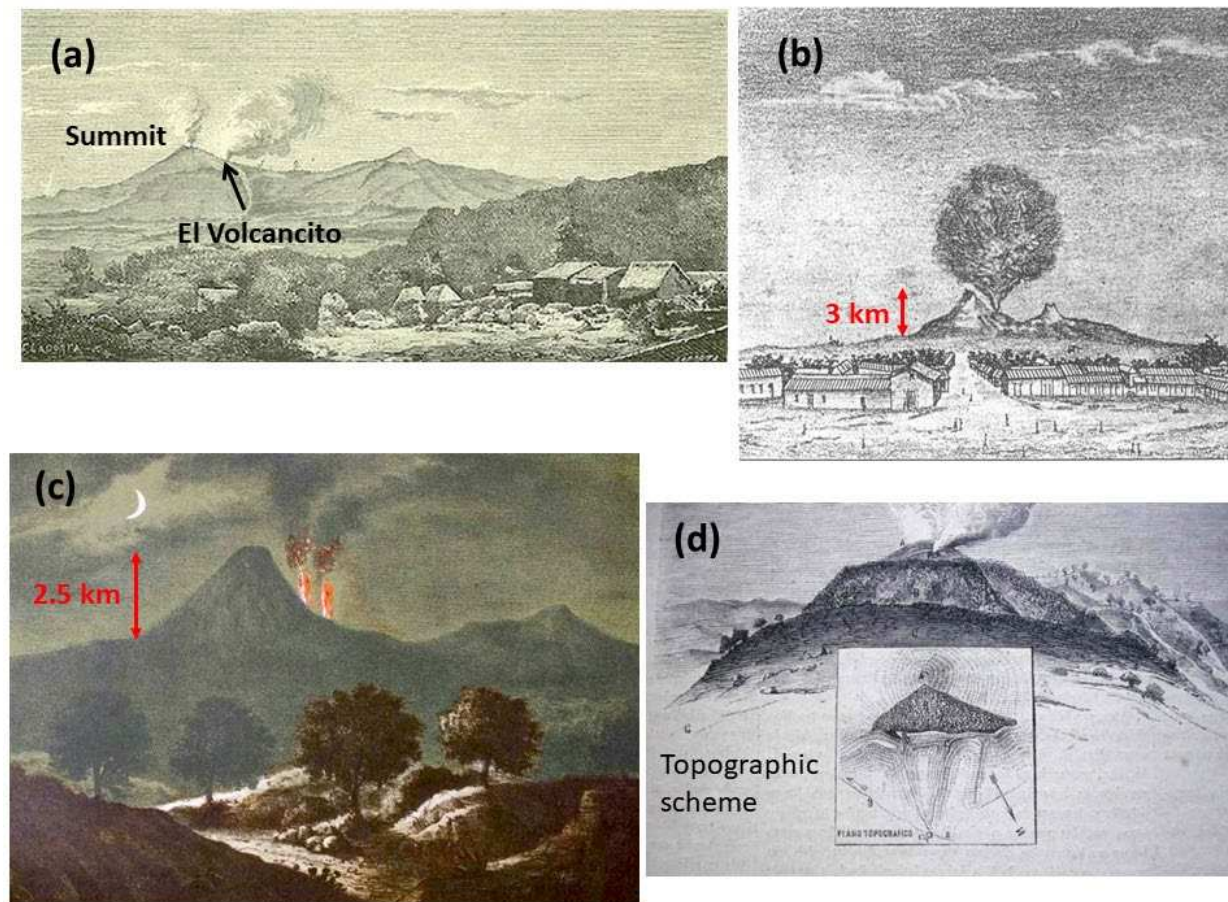
443 4.1.2 Early eruptive period (1869–1870)

444 On 19 March 1869, Mauricio Gómez, the owner of the San Marcos hacienda (< 10 km
445 from the volcano), was warned by one of his employees of “*a hump that was observed towards*
446 *the northeast flank of the volcano*” (literal translation). Shortly thereafter, on 12 June 1869, an
447 eruption occurred, marking the onset of El Volcancito cone formation. This vent was ~1 km
448 from the main crater and ~700 m lower in elevation (Luhr and Carmichael, 1990a,b). As

¹ Exact methodological details are not included in the reports of the French expedition; as such, the accuracy of the data cannot be verified.

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449 depicted in Figure 3a, this eruption occurred simultaneously with persistent activity in the
450 summit area.



451 **Figure 3.** Drawings depicting the onset of the El Volcancito eruption. (a) Engraved image of
452 Volcán de Colima (~1869–1870) showing steam emissions from the main summit crater (left-
453 hand side) and from the new eruptive mouth of El Volcancito (right-hand side). (b) Image of
454 Volcán de Colima, dated 12 June 1869, showing the initial stages of the El Volcancito eruption;
455 the original drawing was made from Tonila by Francisco Rivas, and subsequently reproduced by
456 Bárcena (1887a,b) and Bretón (2002). (c) Iriarte lithograph (1869) showing the onset of activity
457 during the growth of El Volcancito at Volcán de Colima. (d) Engraving (1870) based on the
458 original drawings of Manuel Gómez, made on 22 August 1869, showing the new El Volcancito
459 cone following 2 months of eruptive activity.

460

461 While there is some evidence for a progressive development of volcanic activity (e.g.,
462 thermal and fumarolic activity; Dollfus and Montserrat, 1869a,b), most records suggest that El

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463 Volcancito arose from highly explosive activity. One report describes the initial explosion as
464 *"very big and noisy, hearing a loud thunder that caused fear among the surrounding towns.*
465 *From San Marcos (13.5 km southeast of the top) and Tonila (13.5 km south-southeast of the top)*
466 *very large stones were seen thrown at a great height, which when they fell, rolled down the*
467 *mountain to the ravines that are nearby that course. In the afternoon of that day another great*
468 *eruption occurred that raised a cloud and caused material fall"* (Arreola, 1915; literal
469 translation).

470 Eyewitness accounts, which can sometimes be exaggerated owing to fear and/or observers'
471 perspectives, are supported by pictorial documents and photographs. A drawing dated 12 June
472 1869 (Figure 3b) shows vigorous emissions from a vent to the northeast of the summit; the
473 accompanying notes state that *"[...] the eruption appears in the form of a balloon of steam and*
474 *illuminated by a multitude of lightning flashes and fragments of reddened rocks that were*
475 *detached from the same balloon"* (literal translation; Bárcena, 1887a,b). This drawing is highly
476 illustrative of the dimensions of the first explosion and the accompanying electrical phenomena;
477 from this image, we estimate the height of the eruptive column to be ~6000 m above the vent,
478 assuming a volcano height of 2500 m. It is possible that the paintings could reflect an
479 exaggeration from the painter's point of view. However, comparison of the volcano in paintings
480 with that shown in a photograph taken just a few years later (Figure 4b) suggests that this
481 eruptive column height is realistic. In any case, to avoid overestimation, we report the lower
482 limited for all of our estimated dimensions; that is, higher values can also be inferred from the
483 lithographs and paintings. Another lithograph depicting the early stage of the eruption suggests
484 that at least two concurrent fissures were opened (Figure 3c).

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485 Growth of the new cone was rapid, and by 13 June it was visible to local observers;
486 descriptions of the cone include a "blister" or "wart", and reports indicate strong effusive activity
487 (Waitz, 1932). Volcanic activity remained intense for 2 months, but on 21 August 1869 an
488 engineer and a photographer were able to ascend the volcano to make the first detailed report
489 (Figure 3d): "*The surface of the "mamelon" [mound] is reddish and bristling with spikes of*
490 *capricious figures; a constant column of smoke comes out from its vertex and from some points*
491 *on the slopes of the volcano, white in the middle, bluish on the sides and blackish at the top*
492 *where it later takes the shape of a cloud"* (literal translation). They estimated the height of the
493 new cone to be approximately 300 m. Interestingly, they observed that emissions from the
494 summit crater had ceased; however, on 24 August, as activity at El Volcancito waned, "*columns*
495 *of smoke began to come out of the main crater that formed a great cloud"* (literal translation).
496 The engineer, Manuel Gómez, took detailed drawings and field measurements of the cone, which
497 had a base diameter of ~400 m (Figure 3d; Bárcena, 1887a,b; Arreola, 1915). A subsequent
498 report (Sartorius, 1869) stated that the area occupied by material erupted in the first 2 months
499 covered 20,000 m², and that the top of the new cone was < 100 m lower than the main summit
500 crater (Orozco, 1869; Arreola, 1915). From these data, Waitz (1906) and Mooser (1961)
501 estimated a lava volume of 0.21 km³ after 2 months of activity.

502 Subsequent quiescence at El Volcancito lasted for at least 2 years, during which only
503 sporadic and small-scale lava flows were reported. During this period, the focus of activity
504 returned to the summit crater.

505 4.1.3 Seismic series of 1870–1871

506 The early stage of the eruption does not appear to have been characterized by intense
507 seismic activity; earthquakes are not reported in historical records. However, on 2 November

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508 1870, local chronicles reported *"the earth shook with force even in the port of Manzanillo"*,
509 located 60 km from the volcano. A year later, on 3 October 1871 a seismic series began.
510 Between approximately 03:00 and 06:00 local time, there are reports of at least four strong
511 earthquakes, the first of which included 5 s of shaking. Again, these events were felt as far away
512 as Manzanillo, and were strong enough to cause serious damage to buildings, some of which
513 collapsed, although no casualties were reported. The largest of the events was described as
514 *"oscillated from north to south and lasted about one minute"*. Felt earthquakes continued for at
515 least 1 month, with many observers attributing the activity to Volcán de Colima. This series of
516 event occurred immediately before the reactivation of volcanic activity; however, whether it was
517 a trigger or simply a consequence of pressure accumulation inside the magmatic system requires
518 further consideration (see Discussion section).

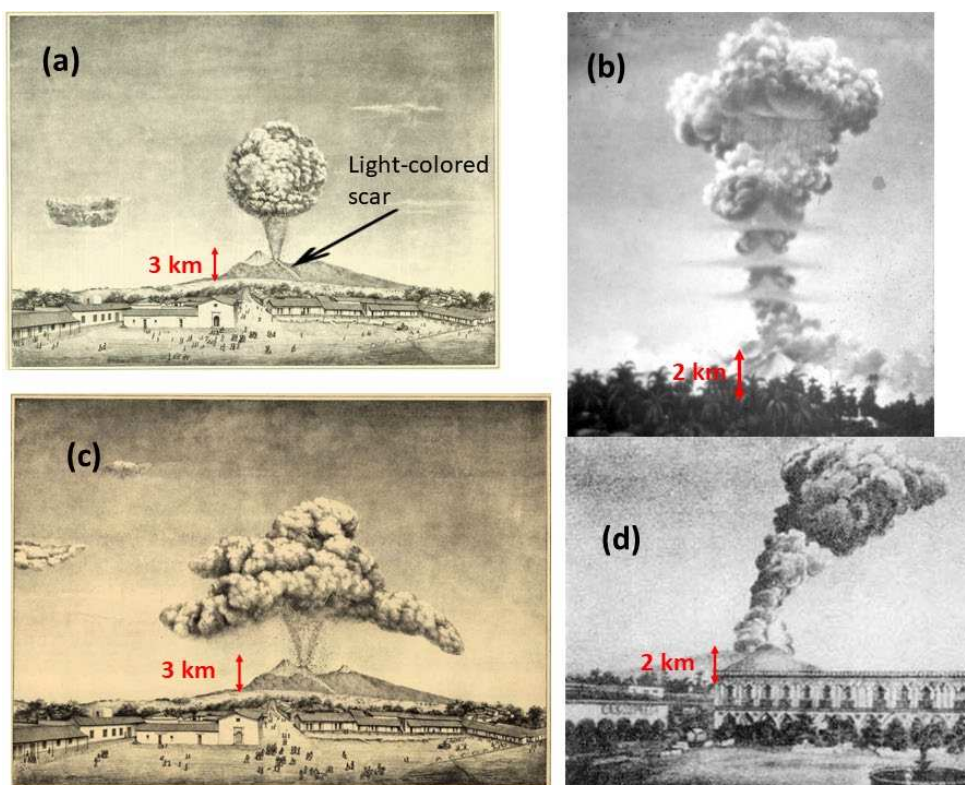
519 **4.1.4 Second eruptive phase (1872)**

520 The second explosive eruptive phase at El Volcancito began in early 1872; based on a
521 drawing by Francisco Rivas (Figure 4a), activity likely started on or around 26 February. The
522 image depicts a tree-shaped eruption cloud, similar to that described in 1869, along with
523 lightning, ash fall, and the emission of pyroclastic material. Using the image of the 1869 eruption
524 as a reference, the new cloud reached a height of > 11 km above the vent. The cone is clearly
525 delimited in the drawing, and the size and force of the explosion appear to be much greater than
526 those of previous events; contemporary reports record scenes of panic and fear, as *"People of all*
527 *classes knelt in the streets and squares asking God for mercy, carrying out public processions of*
528 *penance"* (literal translation of local chronicles). While the image in Figure 4b shows an eruption
529 cloud that has reached neutral buoyancy and is starting to propagate sideways, the column shown
530 in Figure 4c is straight. These differences could reflect different atmospheric conditions.

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531 A light-colored scar on the eastern flank (Figure 4a) probably depicts hot pyroclastic
532 material and ash flowing down the slope. Pyroclastic material with a particle size larger than that
533 of ash fell on populated areas > 10 km from the vent (ECOL, 1872). Our drone based images
534 suggest that the flows travelled 7.5 km from the vent. As in 1869, the historical records suggest
535 that the increased activity from El Volcancito marked a total cessation of activity at the summit
536 crater.

537 Between 8 and 19 March of the same year, explosive activity was on-going, and may have
538 increased in intensity (Bárcena, 1887a,b; Orozco and Berra, 1888; Arreola, 1915); ash and
539 pyroclastic material were frequently deposited around the volcano. Figure 4b shows an early
540 photograph of an explosion on 19 March 1872; based on the distance from the volcano, the
541 height of the pictured eruptive column may have exceeded 7,500 m above the vent.



542 **Figure 4.** Pictures and photographs of the second eruptive period. (a) View of Volcán de Colima
543 at 10:30 local time on 26 February 1872, showing the onset of the second stage of explosive

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544 eruptive activity from the new El Volcancito cone; this drawing was made by Francisco Rivas
545 from the tower of the parish church in Tonila. **(b)** Photograph by Manuel Gómez, taken from the
546 center of Colima city on 19 March 1872, showing an eruptive column from Volcán de Colima.
547 **(c)** Picture of the explosion on 19 March 1872 at 19:30 local time showing a view from Tonila
548 village (painted by Francisco Rivas). **(d)** Photograph taken from the city of Colima by Manuel
549 Gómez at 12:00 local time on 13 August 1872, showing the renewal of explosive activity from
550 the El Volcancito cone; image from the historical archive of the Municipality of Colima, and
551 reproduced by Bárcena (1887a,b), Arreola (1915), and Bretón (2002).

552

553 Based on the intensity of the eruption and clear incandescence, residents of the city of
554 Colima, located > 25 km from the volcano, thought that this new explosive activity was
555 associated with the opening of new eruptive craters. Incandescence observed from the cities of
556 Colima and Zapotlán was possibly associated with a lava fountain whose height exceeded that of
557 the volcano summit (i.e., > 500 m above the vent; Arreola, 1915). Intense explosive activity
558 continued for at least 1 month more, with ash fall covering a wide geographical area (Bárcena,
559 1887a,b; Orozco and Berra, 1888; Arreola, 1915) and the evacuation of communities from
560 around the volcano (e.g., the small town of Quesería) owing to the appearance of incandescent
561 cracks, the emission of volcanic bombs, and the ignition of crops. These reports are consistent
562 with intense lava fountaining, lateral fissures within the new crater, and the formation of
563 pyroclastic flows.

564 As in 1869, strong seismicity was not reported until late in the eruptive period. On 28
565 March 1872, strong shaking was reported (Zayas, 1893, cited in García Acosta and Suarez,
566 1996), but it is not clear if this was seismic in origin, or simply associated with a particularly
567 violent explosion also reported at this time.

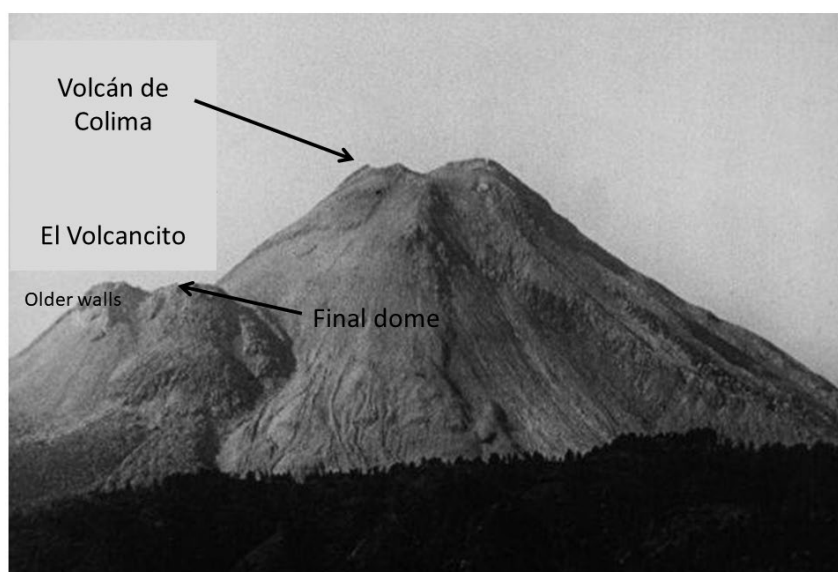
568 After a few months of relative calm, explosive activity returned on 13 August 1872. A
569 photograph from 13 August (Figure 4d) shows the intensity of this activity; aside from the large
570 size of the eruptive column, a large pyroclastic flow is apparent. Ash (probably very fine) from

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571 this event travelled large distances, with reports of a darkened sky and ash fall > 170 km from
572 the vent, such as that in the city of Autlán (Arreola, 1915).

573 4.1.5 Third eruptive phase (1873–1877)

574 Between August 1872 and March 1873, contemporary reports record 10 significant
575 explosions (Arreola, 1915), with the last on 27 March 1873. As with the previous eruptive
576 episodes, activity at Colima summit ceased. From April 1873 to 1877, reports of activity are
577 limited to sporadic minor explosions, moderate lava emissions, and fumarolic activity (Bárcena,
578 1887a,b; Arreola, 1915; Bretón, 2012), along with a renewal of activity at the summit crater. In
579 addition, there are reports of small felt earthquakes, with descriptions such as "*noises and*
580 *movements coming from the interior of the earth*". Between 18 October and 27 November 1877
581 there were two further eruptive episodes or explosions, one of which was recorded in a drawing
582 by Manuel Gómez and the other described by local reports. The drawing shows a column
583 emerging from the main crater and rising to ~2,000 m above the vent (Bretón, 2012).



584 **Figure 5.** Photograph of Fuego de Colima and the parasitic El Volcancito cone in ~1907 (image
585 stored in the Gerd Kohler Archive).

586 This change in activity back toward the summit area is the milestone we used to define the
587 end of the eruptive period (i.e., 1869 to 1877). We have identified no evidence of volcanic
588 activity at El Volcancito after 1877. In a photograph taken in 1907 (Figure 5), the morphology of
589 El Volcancito differs from that of classic monogenetic cinder cones, with the edifice more in-
590 keeping with a central cone or dome. Multi-generational features are visible, including older
591 walls and a final dome structure in the center. Lava flows are evident, and appear to be thicker
592 than other flows found around the Colima Volcanic Complex. Both El Volcancito and Volcán de
593 Colima share similar slopes; therefore, the thicker flows from El Volcancito suggest magma with
594 a relatively higher viscosity than that erupted from the main edifice.

595 **4.2 Lava volume estimation**

596 Our analysis of historical records suggests that the El Volcancito eruption was longer and
597 much more voluminous than previously thought. Previous estimations of the emitted volume of
598 the El Volcancito eruption were performed by Waitz (1906) and Mooser (1961) based on data
599 from Manuel Gómez in August 1869. These calculations assumed a cone with a height and base
600 diameter determined a few months after the beginning of the eruption. In contrast, we applied
601 modern methods, including the use of drone imagery, to obtain the whole dimension, including
602 the main edifice and associated lava flows, produced across the full eruptive period (1869–1877).
603 We were unable to include the volume of ash within this calculation owing to a lack of available
604 information (see section 3.2 Volume estimation).

605 Using the Prismoid method, El Volcancito was divided into 14 prismoids (from 2250 to
606 3561 m a.s.l.). Over each volume we applied equation (1); the results are shown in Table 1. The
607 total calculated volume was found to be $7.997 \times 10^8 \text{ m}^3$. Using the “convhull” function, the total
608 calculated volume was found to be similar ($8.076 \times 10^8 \text{ m}^3$). Even without considering material

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609 emitted into the atmosphere, the El Volcancito eruption represents one of the largest known
 610 historical lava deposits for Volcán de Colima.

611 **Table 1.** El Volcancito cross sectional areas (at 50-m elevation intervals) and volumes (at 100-m
 612 elevation intervals) using the prismoid method

Prismoid #	Elevation range (m a.s.l.)	Area (m ²)	Volume (m ³)	Prismoid #	Elevation range (m a.s.l.)	Area (m ²)	Volume (m ³)
1	2250	3,907.67	1,890,274.45	9	3050	2,026,210.00	86,764,750.00
	2300	17,848.60			3150	1,638,390.00	
2	2350	38,114.40	7,543,889.97	10	3100	1,832,000.00	202,940,875.00
	2400	75,077.00			3200	1,389,530.00	
3	2450	114,211.00	17,961,800.00	11	3250	727,515.00	44,690,116.70
	2500	182,262.00			3300	416,262.00	
4	2550	234,449.00	29,229,833.30	12	3350	288,844.00	20,677,900.00
	2600	292,913.00			3400	204,709.00	
5	2650	347,689.00	41,325,133.30	13	3450	132,994.00	7,386,170.61
	2700	415,296.00			3500	75,585.10	
6	2750	470,635.00	53,112,033.30	14	3550	7,835.83	29,022.79
	2800	531,739.00			3561	150.51	
7	2850	589,131.00	64,801,633.30		3561	115.51	
	2900	644,413.00			3561	339.38	
	2950	721,315.00			3561		
8	2950	2,361,850.00	221,311,000.00	TOTAL		799,664,432.72 m³	
	3000	2,222,650.00				7.996 x 10⁸ m³	

613 5 Discussion

614 5.1 Eruptive model

615 With one exception, explosive historic eruptions of Volcán de Colima have all been from
 616 the summit crater, including those in 1818 (sub-Plinian, VEI 4), 1889 (VEI 4), 1885 (VEI 3),
 617 1903 (VEI 3), and 1913 (sub-Plinian, VEI 3–4). These events saw no apparent changes in
 618 magma composition (Crummy et al., 2014, 2019a,b) or volcano dynamics (Bretón et al., 2002).
 619 Moreover, over such a short time period (<100 years), it seems unlikely that there were
 620 significant but temporary changes to the main magma plumbing system. As such, the El

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621 Volcancito eruption represents an unique event that can only be explained by transient external
622 influences acting on the volcanic system. To build our model of the eruption (Figure 6), we
623 considered 11 main lines of evidence.

624 (1) In 1845 and 1858 two large regional earthquakes ($M_w > 8.0$) affected the volcanic
625 structure. (2) Thermal and fumarolic activity observed in 1866 was consistent with the future site
626 of El Volcancito. (3) The eruption "officially" started 1869, with reports of a large explosion
627 along with 'smoke' and/or lava; at the same time, summit activity ceased. (4) Over 4 months of
628 intense volcanic activity, there are reports of two lava fountains followed by several big
629 explosions, pyroclastic flows, and growth of the new edifice. (5) In 1870 and 1871 activity was
630 low; however, from late 1870 through 1871, a local seismic series with events of moderate
631 magnitude occurred. (6) In 1872, activity returned to El Volcancito with a series of large and
632 frequent explosions (the largest of the whole 8-year eruption); there is also evidence for large
633 lava fountains, dome construction, and effusive lava flows. (7) In 1873 and 1877, several large
634 explosions with pyroclastic flows and other effusive episodes occurred. (8) The end of the
635 eruption was marked by a summit explosion on 18 October 1877. (9) The morphology of El
636 Volcancito shown clear signs of multiple constructive and destructive events. The external rim
637 had a classic "toothed structure" with a central dome and a lava flow running through a collapsed
638 section of the crater wall. (10) The erupted materials are petrologically distinct from those in
639 1913 and 1818 (despite shared explosivity), but petrologically similar to summit dome eruptions
640 (despite being dynamically much more vigorous); however, their unique trace element signature
641 suggests the external addition of excess fluids and assimilation of hydrothermally altered wall
642 rock immediately prior to eruption. (11) According to our re-evaluation, the total volume of

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654 regional earthquakes of 1845 and 1858. Subsequently, magma-water interaction along the
655 Tamazula Fault and/or at an aquifer controlled the eruptive dynamics.

656 Many studies have suggested interaction between large earthquakes and volcanic eruptions,
657 with possible long-distance triggering mechanisms including: a) changes in the state of the
658 magmatic system (e.g., Díez et al., 2005); b) dynamic stresses induced by seismic waves from
659 the triggering earthquake (e.g., Prejean and Hill, 2018); c) processes along local faults (e.g.,
660 Roman and Heron, 2007); d) static or quasi-static stress changes (e.g., Hill et al., 2002); and
661 stochastic models (e.g., Bebbington and Marzocchi, 2011). Seropian et al. (2021) suggest that
662 volcanic unrest triggered by large earthquakes is particularly common when hydrothermal
663 systems are present in the reservoir area. In terms of El Volcancito, it is plausible to assume that
664 the 1845 and 1858 earthquakes altered the state of stress on the Tamazula Fault. Increased brittle
665 behavior along the fault plane, which reaches depths of nearly 12 km (Pacheco et al., 2003) or up
666 to 40 km (Sychev et al., 2019), would have caused changes in the local stress field and created
667 conditions conducive to magma ascent along newly created pathways. The French expedition
668 reported fumarolic fields in 1866, some of them located where El Volcancito subsequently grew.
669 This location is directly above the vertical projection of the Tamazula Fault, based on satellite
670 images of surface features, the distribution of waterways (including rivers, streams, and creeks),
671 and micro tectonic analysis of failure and stress and their association with the Colima Volcanic
672 Complex (Garduño et al., 1998).

673 Based on the compositions and textures of the erupted products, the initial eruption pulse at
674 El Volcancito sampled a similar magmatic source as the pre- and post-El Volcancito magmas
675 erupted from summit area domes (Savov et al., 2008). We suggest that the large regional
676 earthquakes opened a zone of structural weakness (allowing for new conduit formation) and

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677 facilitated interaction between zones rich in volatiles (H₂O) and andesitic magmas at depth.
678 Based on analysis of amphibole reaction rim thicknesses, Atlas (2001) and Atlas et al. (2006)
679 suggested that magma ascent below El Volcancito began ~4 months prior to the eruption.
680 However, the explosive initial eruption followed by fissure-style activity is indicative of sudden
681 depressurization of the system. The elevated abundances of fluid immobile rare earth elements
682 (REE) and evidence for assimilation of hydrothermally altered materials (e.g., clays and zeolites)
683 indicate magma interaction with fluid-modified fault and/or aquifer wall rock at the base of the
684 volcano. The introduction of fluids from wall rocks and/or an aquifer explain the explosiveness
685 of the magma. Moreover, as there was no pre-existing impermeable volcanic plug near the
686 surface, the volatile rich 1869 magma (Luhr and Carmichael, 1980) had no obstacles, resulting in
687 the unusually tall lava fountaining (Figure 2c).

688 Consequently, this relatively brief activity was followed by the arrival of the degassed and
689 cooled (highly crystalline) portion of the initially volatile rich melt batches, which intermittently
690 plugged the conduit and/or feeder dyke(s), resulting in dome formation and destruction via large
691 explosions following the initial 1869 activity. During the first eruptive period, as the weight of
692 the El Volcancito structure increased, the hydrostatic pressure of the system also rose. Together
693 with the fluid-enriched nature of the magma and the contribution from groundwater, this drove
694 the continuation of activity. Excess fluids can cause magma fragmentation and an increase in
695 pressure, and this activity was characterized by explosive eruptive episodes (Strombolian to sub-
696 Plinian) interspersed with lava effusion and longer periods of quiescence. Similar eruption
697 temperatures between the El Volcancito and other Volcán de Colima eruptions (940°C and
698 1052°C; Atlas, 2001) suggests that the switch between dome building and lava flow activity was

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699 not due to cooling of the conduit/dykes, further supporting the hypothesis that the switch may
700 have been due to an interruption in the external supply of fluid/volatiles.

701 Interaction with water likely also played an important role in the explosive period of 1872.
702 We suggest that the seismic series of 1870–1871 either caused or was the consequence of
703 hydraulic stress-driven elastic processes driven by water-magma interaction in the shallow
704 reservoir. As indicated by Díaz-Moreno et al. (2015) we suggest that this seismic swarm
705 represents the response of the upper crust to stress perturbations with pulsatory character, linked
706 to the interaction of the magma with the surrounding faulting systems and with the water. Since
707 there is no correlation with rainfall events, we assume that the reservoir was not the local water
708 table but a deeper body (~3–4 km below sea level), as suggested by Palo et al. (2009). Despite
709 the large explosions, historical evidence confirms that the magma volume of this later-stage of
710 activity was lower than that of the opening stages of the eruption.

711 The final stage of activity between 1874 and 1877, including both destructive explosions
712 and constructive lava flows, formed the final shape of the El Volcancito cone. After 8 years of
713 intermittent activity, the eruption of El Volcancito ceased in 1877. We suggest that the cessation
714 of activity marked the point at which the weight of the El Volcancito structure exceeded the
715 overpressure of the accumulated magma; at this point, magma followed the path of least
716 resistance back to the main summit structure.

717 Our hypothesized model differs from the "classical" eruptive model proposed for Volcán
718 de Colima in two critical ways. First, we emphasize the probable role of regional earthquakes in
719 changing the local stress conditions along the Tamazula Fault system, resulting in new conduits
720 for magma ascent. Second, we give weight to the role of water in continuously modifying the

721 eruptive dynamics, resulting in activity that alternated between classical effusive mechanisms
722 and more explosive sub-Plinian explosions (i.e., water driven eruptions).

723 Based on our new calculations, the large volume (0.8 km^3) emitted volume during the El
724 Volcancito eruption warrants its classification as a moderate–large volcanic event (VEI 4–5). In
725 comparison, the widely studied 1818 and 1913 eruptions, both considered large and explosive
726 eruptions, were assigned as VEI 3–4. The eruptive volume is similar to that produced by the
727 1980 Mt St Helens eruption (1 km^3), and while these events differed in eruptive mechanisms and
728 phenomena, we offer this comparison to highlight the size and importance of the El Volcancito
729 eruption within the catalog of historical eruptions at Volcán de Colima specifically, and within
730 North America more generally.

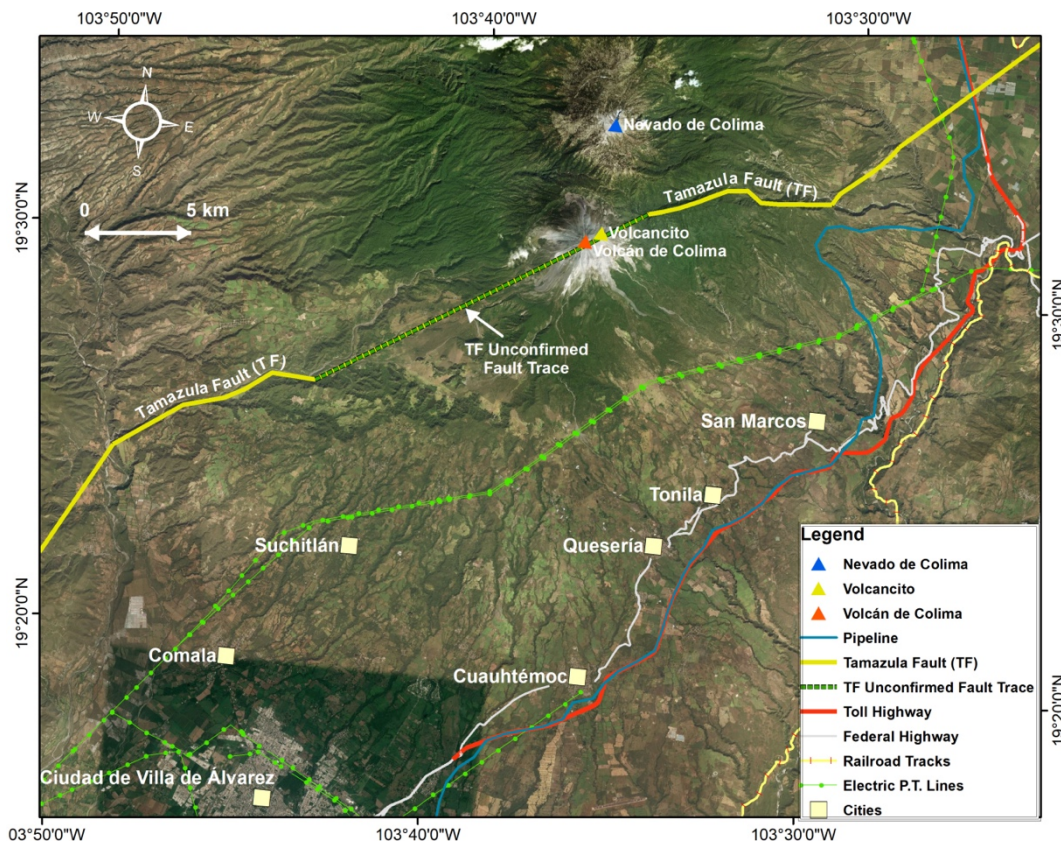
731 **5.2 Implications for volcanic risk**

732 While the role of water in driving so-called mega-eruptions (e.g., Toba or Yellowstone;
733 Huang et al., 2015; Shapiro and Koulakov, 2015; Koulakov et al., 2016, 2019) is well
734 documented, the potential for minor eruptions to become highly energetic as a consequence of
735 water driven action is not widely acknowledged. Fissure and/or flank eruptions are typically
736 monogenetic; however, as is clear from the growth of El Volcancito, these events are not always
737 minor, despite the widespread assumption to the contrary, and can include multiple eruptive
738 stages. Given the complexity of the factors controlling their onset and location, together with the
739 unpredictable nature of water-magma interaction, the modeling of potential eruptive dynamics,
740 locations, and timing is challenging. This has serious implications for hazard and risk
741 management, particularly at volcanoes located close to major population centers. Numerous such
742 volcanic systems (e.g., Vesuvius and Naples, Popocatepetl and Mexico City, Etna and Catania)

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743 exhibit evidence for monogenetic flank eruptions that have affected areas that are now centers of
744 population and/or infrastructure.

745 From the point of view of local and regional volcanic risk, numerous towns and cities are
746 found near Volcán de Colima, within both Colima and Jalisco states (Figure 7). In total, close to
747 a million people live within the area most impacted by eruptions from Colima. The closest
748 settlements are at risk from lava, pyroclastic, and debris flows; while a larger area is at risk from
749 lahars and ash fall. Towns that would be directly threatened by a resurgence of activity at El
750 Volcancito include Cuauhtémoc and Quisería in Colima State, and Tonila, San Marcos, and El
751 Platanar in Jalisco State (Figure 7); together, these towns account for 28,000 residents. Ash fall
752 over a larger area could directly affect larger cities (e.g., Colima, Villa de Alvarez, Tecomán, and
753 Manzanillo in Colima State, and Ciudad Guzmán in Jalisco State).



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755 **Figure 7.** Main areas of risk around Volcán de Colima in terms of human settlements, land
756 transport systems, and other vital infrastructure (e.g., electricity and gas).

757
758 In terms of major and critical infrastructure within the main hazard area, the Direct Federal
759 Highway of Toll 54-D (interestingly called the “Transvolcánica” highway), connects Manzanillo,
760 Colima, and Guadalajara and passes less than 15 km from the summit (Figure 7). The port of
761 Manzanillo is one of the largest container ports on the Pacific coast of North America, and is
762 connected by road and rail to other parts of Mexico, the USA, and Canada. For example, the
763 railway line of the Ferromex company² (Port of Manzanillo to Guadalajara city), which moved
764 12,621 million tons/km in the first quarter of 2020, passes less than 18 km from the summit of
765 Volcán de Colima. The threat to these supply routes is particularly noteworthy given the large
766 amount of hazardous material transported by these systems, including organic and inorganic
767 chemicals, petrochemicals, synthetic resins (plastics), and fertilizers, among others. Finally, in
768 terms of air transport, the Colima and Manzanillo airports are located ~40 and 70 km from the
769 Colima summit, respectively. The region also has four smaller airports (mainly used by private
770 planes). Ash fall would significantly impact or even stop operations at these facilities. Moreover,
771 a sustained period of activity that introduced ash into the atmosphere would have a serious
772 impact on air traffic around North, Central, and South America.

773 Two other critical infrastructures that cross near the volcano are high- and medium-voltage
774 power lines and a gas pipeline. High voltage power lines (230 and 400 kV) originating from the
775 Manzanillo Thermoelectric Power Plant provide electricity that is used nationwide; they run less
776 than 7.5 km from the summit of Volcán de Colima. The Segment 2 LNG Manzanillo–
777 Guadalajara gas pipeline transports natural gas from Vessel 2 of the Cuyutlán Lagoon. Pipelines
778 of the Manzanillo Liquefied Natural Gas Terminal run parallel to Federal Direct Toll Highway

² <http://www.ferromex.com.mx/ferromex-lo-mueve/sistema-ferromex.jsp>

779 54-D, less than 10 km from the volcano; with a length of 310 km and a diameter of 24/30 inches,
780 this pipeline has a capacity of 360–500 million cubic feet per day, and transports natural gas to
781 locations around the country.

782 **6 Conclusions**

783 We used evidence from published studies and historical sources to determine a new
784 perspective on the eruptive processes of the parasitic El Volcancito cone at Volcán de Colima.
785 We have found that the formation of El Volcancito was a highly energetic process involving
786 multiple distinct eruptive episodes. Local settlements were significantly impacted by pyroclastic
787 deposits; moreover, ash injected into the atmosphere affected populations up to 150 km from the
788 volcano, with ash fall recorded at locations even more distant. The volume of material emitted
789 was at least four times higher than suggested by initial calculations (0.8 vs. 0.21 km³); being the
790 largest historical volume for this volcano. Moreover, we have found evidence for at least 10
791 large explosions with eruptive columns of > 6 km during an interval of ~8 years; in some cases,
792 the columns could reach up to 10 km above the vent. This is in contrast to previously published
793 works that state the cessation of activity in 1872, after just 3 years.

794 Petrological evidence for the eruption trigger rules out volatile addition via mingling and
795 mixing, as seen in 1818 and 1913, and thought to be the main mechanism for erupting most high
796 volatile magmas. Instead, we suggest that the eruption was influenced by two large regional
797 earthquakes (Mw > 8.0) that simultaneously opened a zone of structural weakness (allowing for
798 new conduit formation) and facilitated interaction between zones rich in volatiles (H₂O) and the
799 andesitic magmas stored near the base of the volcano. The main contribution of this work is to
800 demonstrate that under the right conditions, flank or monogenetic eruptions can demonstrate this

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801 highly energetic behavior, which has serious consequences for volcanic risk and hazard
802 management at local, regional, and global scales.

803 In particular, we want to highlight the importance of historical and archival evidence in
804 understanding volcanic hazards. In general, historical records are underestimated or often
805 considered of low scientific value when attributed to "non-specialist" observers. Many
806 researchers unfamiliar with historical data consider that these written or graphic testimonies are
807 always influenced by popular beliefs, fears, or superstitions, and are therefore not credible or of
808 sufficient scientific weight. However, historical and mythological studies have permitted better
809 understanding of volcanic phenomena throughout human history (e.g., Sigurdsson 1999;
810 Cashman and Giordano, 2008; De Boer and Sanders, 2012; Lavigne et al., 2013; Nunn, 2014;
811 Troll et al., 2015; Oppenheimer et al. 2018). In the context of this study, we believe that the
812 historical data are as valid as other scientific data sources based on four main observations. (1)
813 The historical records include multiple references to the same volcanic phenomena (i.e., similar
814 observations and testimonies). (2) Among the different types of historical document (paintings,
815 lithographs, and writings) there is substantial agreement when describing volcanic phenomena;
816 these documents were created at a time when the dissemination of news was not as extensive as
817 it is now, and the possibility that observations were based second-hand information rather than
818 direct observation is low. (3) The records and images within the historical archive clearly depict
819 typical observables of volcanic phenomena. (4) The archives include some of the earliest known
820 photographic images of a volcanic eruption.

821 Volcán de Colima is considered a "living petrological laboratory" owing to the large
822 volume of available data. By reviewing these data alongside evidence from historical records, we
823 are able to consider the system from a new perspective. It is our hope that this study will inspire

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824 other investigations of historical records, which will perhaps reveal other underestimated events
825 that have passed out of interest but which may have implications for volcanic risk.

826 **Conflict of Interest**

827 The authors declare that the research was conducted in the absence of any commercial or
828 financial relationships that could be construed as a potential conflict of interest.

829 **Author Contributions**

830 **Mauricio Bretón:** Supervision, Conceptualization, Methodology, Investigation, Writing -
831 Original Draft. **Jesús M. Ibáñez:** Supervision, Conceptualization, Methodology, Translation
832 from the original Spanish to English of the observations of the eruptive process, Investigation,
833 Writing - Original Draft. **Zoraida León:** Investigation, Formal analysis, Visualization. **Imelda**
834 **Plascencia:** Investigation, Formal analysis, Visualization. **Arnoldo Campos:** Investigation,
835 Formal analysis. **Hydyn Santiago:** Investigation, Formal analysis. **José Armando Téllez:**
836 Investigation, Formal analysis. **Ivan Savov:** Investigation, Formal analysis. **Silvio de Angelis:**
837 Formal analysis, Writing - Review & Editing.

838 **Data Availability Statement**

839 The original data and documents used for the historical review of the present work are available
840 from the historical archive of the Volcanological Observatory of the University of Colima; the
841 historical archive of the Municipality of Colima (AHMC); the graphic art collection of Munich,
842 Germany; the Banamex Cultural Development Collection; the historical archive of the
843 Archbishopric of Zapotlán, Jalisco; the National Photo Library of Mexico; the Bulletin of the
844 Statistical Geographical National Institute of the Mexican Republic; The National Hemeroteca of
845 Mexico; and the Official Gazette of the state of Colima. El Volcancito dome sample

846 geochemistry, along with that of other dome samples, is provided as a supplement in Savov et al.
847 (2008).

848 **Acknowledgments**

849 We would like to thank Janire Prudencio for the realization of Figure 6 and Sebastian González
850 for his support in the satellite image processing. Satellite images used in Figure 1 and Figure 7
851 were acquired by the University of Colima from Digital Globe 2018 via the Web Map Service
852 (WMS). We are especially grateful to the editor, Diana Roman, and to Gilles Seropian and an
853 anonymous reviewer for their insightful comments and suggestions, which significantly
854 improved this manuscript. English language editing was performed by Tornillo Scientific.

855 **Funding**

856 This work was partially supported by the FEMALE project of the Spanish Government [grant
857 number PID2019-106260GB-I00].

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1189

1190 **Appendix A.**

1191 Original Spanish source text used as historical evidence for the eruption of El Volcancito.

1192 Translation was performed by Jesús M. Ibáñez.

1193

1194 *1. On how the 1845 earthquake was felt and the damage to the main edifice of Volcán de Colima.*

1195 “[...] notándose desde Tuxpan haberse derrumbado del cráter del volcán de Fuego, enormes
1196 masas que se veían rodar por el rumbo de Cofradía de Tonila, levantándose una polvareda que
1197 cubrió todo el cerro”.

1198 “[...] por Colima y pueblos adyacentes se advirtió en esos días un ruido extraordinario como de
1199 grandes masas que se desprenden del interior de la tierra y se precipitan en un gran lago de agua
1200 de mucha profundidad”.

1201

1202 *2. On the eruption onset.*

1203 “Se observó una entumescencia que se observaba hacia el flanco noreste del volcán”

1204 “La explosión inicial fue muy grande y estrepitosa, escuchándose un fuerte trueno que causó
1205 temor entre los pueblos comarcanos”.

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1206 “Se vieron piedras muy grandes lanzadas a mucha altura, las cuales al caer rodaban por la
1207 montaña hasta las barrancas que hay por ese rumbo”.

1208 “Por la tarde de ese día ocurrió otra gran erupción que levantó una nube y provocó caída de
1209 material”.

1210 “Al principio se creyó que las columnas de humo eran ocasionadas por el incendio de algún
1211 monte; pero al entrar la noche se vio que eran efecto de la erupción del volcán, pues se
1212 percibieron las detonaciones subterráneas, el fuego y las masas incandescentes que brotaban de
1213 aquel lugar.”

1214 “La erupción causó pavor por el mucho fuego que se veía entre la nube y por las rocas
1215 incandescentes que rodaban sobre la montaña”.

1216 “[...] y aparece la erupción bajo la forma de un globo de vapores y alumbrado de multitud de
1217 relámpagos y fragmentos de rocas enrojecidas que se desprendían del mismo globo. Aunque del
1218 cráter principal, que se halla en la cima del gran cono, brotaban algunas humaredas, esta
1219 erupción se estaba efectuando sobre una abertura hecha sobre el mismo cono, un poco debajo de
1220 la cúspide y en la región noreste”.

1221 “El día 13 de junio ya se podía observar desde la hacienda de San Marcos la formación de una
1222 “ampolla” que crecía rápidamente por un costado del cono superior, abriéndose grietas y
1223 saliendo lava en bloques, que al principio solamente se amontonaban en el lugar”.

1224 “La superficie del mamelón es rojiza y erizada de picos de figuras caprichosas; de su vértice y de
1225 algunos puntos de las vertientes del volcán sale una columna de humo constante, blanca en el
1226 medio, azulada a los lados y negruzca a la parte superior donde luego toma la forma de nube”.

1227 “...de su cima sale una columna de humo constante y de varias partes de los otros puntos,
1228 desprendimientos de vapores que luego se disipan”.

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1229 “[...] el nuevo cráter tenía ya en su contorno un inmenso promontorio de rocas incandescentes,
1230 esparramado en el ancho espacio que antes ocupaba la meseta de Las Playitas, y elevándose a
1231 300 metros de altura, según cálculo de los mismos observadores. El montón de rocas avanzaba
1232 de dos a seis metros por día y sus contornos eran acantilados, lo que ayudaba a su avance, pues
1233 las masas de rocas se desgajaban, y rodando por las pendientes del promontorio, producían
1234 derrumbamientos en diversas direcciones”.

1235

1236 *3. On the lack of volcanic activity in the main central crater of Volcán de Colima.*

1237 “... las rocas incandescentes caían hacia la barranca de San Marcos; del promontorio nuevo se
1238 levantaba una enorme columna de vapor, mientras que del cráter principal salía una ligera
1239 humareda”.

1240

1241 *4. On the eruptive pause of 1870–1871.*

1242 “... la actividad entró en una quietud relativa o más bien puede decirse que se conservó en un
1243 estado latente de erupción sin presentar notables manifestaciones en los años de 1870 y 1871”.

1244

1245 *5. On the re-start of the eruption in 1872.*

1246 “El 26 de febrero de 1872 a las 10:30 am comenzaron una nueva serie de erupciones, elevándose
1247 en pocos minutos una nube en forma de árbol que en poco tiempo adquirió gran altura, tomando
1248 dirección noroeste del volcán. La erupción pudo contemplarse por espacio de dos horas y,
1249 aproximadamente una hora después de iniciada, comenzó a llover en Zapotlán arena de grano
1250 mediano grueso y después de esto un polvo muy fino, ocurriendo lo mismo en San Gabriel,
1251 Tonila y el rancho de La Joya”.

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1252 “Las gentes de todas clases se hincaron en las calles y plazas pidiendo a Dios misericordia
1253 realizando procesiones públicas de penitencia”.

1254 “Se dice que el volcán se bañó de fuego al arrojar peñascos incandescentes, además de provocar
1255 una lluvia de ceniza que cayó en San Marcos”.

1256 “[...] las vistas tomadas en esa fecha muestran una columna elevadísima de vapor, flamas que
1257 brotan del cráter nuevo y grandes peñascos enrojecidos que fueron lanzados muy alto,
1258 alcanzando a caer hasta el lado opuesto sobre el flanco sur.”

1259 “Después de la erupción, por algún espacio de tiempo, se vio desde Colima y Zapotlán una gran
1260 llama que sobrepasaba la cima del volcán, por lo cual se puede inferir que su altura era de más de
1261 quinientos metros”.

1262 “Se inflamó el volcán de fuego a las ocho de la mañana”.

1263 “La segunda erupción fue más intensa y ocurrió a las 8:45 am del día 28, provocando lluvia de
1264 arena gruesa sobre San Marcos, produciendo sobre las hojas de los árboles el mismo ruido que la
1265 lluvia fuerte”.

1266 “El señor D. Ochoa da cuenta de una gran erupción a las 9:00 am y agrega que el volcán arrojó
1267 lodo y ceniza, lloviendo arena en San Marcos y Tonila. Ese mismo día, Manuel Gómez Z. dibujó
1268 otra gran erupción que se efectuó a las once de la mañana, que generó una columna eruptiva
1269 inclinada hacia el este, provocando lluvia de cenizas en los pueblos ubicados en esa dirección
1270 hasta Zapotlán. Se dice que por haber llovido este día tanta arena, el Miércoles Santo se había
1271 convertido en miércoles de ceniza”.

1272 “Una inmensa columna en forma de árbol se levanta del cráter secundario, y en su tronco se
1273 encuentra cortada a distancias iguales por nubes estratificadas”.

1274

Development of El Volcancito

1275 *6. On the volcanic activity after 1872.*

1276 “Continuaron los eventos el día 27 de febrero a las tres de la mañana. Ocurrió otro más el 14 de
1277 marzo a la 6:25 pm donde se vio una línea de fuego semejante a la huella que tras de sí deja un
1278 cuerpo incandescente. A las ocho de la noche se reportó caída de ceniza en la ciudad de Colima,
1279 y al amanecer se vio Colima todo encenizado y se pudo recoger media onza de cinerita en una
1280 vara cuadrada”.