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# Artistic and literary evidence of eruptive activity at Mt. Vesuvius during the apparent long quiescence period before the 1631 eruption

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Vesuvius is among the volcanoes with the highest risk worldwide due to the dense urbanization of its surroundings. Its eruptive history is well documented from 1631 onward, but the period before that, especially the 15th and 16th centuries, is poorly constrained. During this time, the volcano is thought to have experienced a prolonged quiescence, although several reports of activity exist. These reports, however, have generally been considered too uncertain to be included in official eruptive chronologies. In this study, we critically re-evaluate accounts of Vesuvius activity in the 16th centuries in light of recent research and historical-artistic evidence. We identify interesting features of the volcanic activity during this period, before the major 1631 eruption. This analysis not only sheds light on a poorly understood period of Vesuvius eruptive history but also demonstrates that the high intensity of the 1631 eruption cannot simply be attributed to prolonged repose. It thus reinforces the idea that future eruption magnitude cannot be reliably predicted based on the duration of quiescence alone. Moreover, our results indicate that the activity of Vesuvius intersects with that of the nearby Campi Flegrei caldera, highlighting that the behaviour of the two Neapolitan volcanoes during the 16th century was concurrent.

Volcanic risk mitigation in a mega-city environment presents significant challenges worldwide. Mega-cities are characterized by high population densities, complex infrastructures, and rapid urban development. These environments concentrate critical economic, social, and political functions, making them particularly vulnerable to natural hazards such as volcanic eruptions. The ability to formulate reliable scenarios of future eruptions to protect populations exposed to volcanic risk in such contexts requires the integration of multidisciplinary approaches, including physical and mathematical simulations of potential eruptive processes and the most detailed possible reconstruction of the eruptive history of volcanoes. Studies of eruptive history can also benefit from historical and artistic analyses. These approaches can be particularly valuable in regions with a long history of human settlement, where communities have coexisted with volcanic threats for centuries. This long-term interaction has left numerous traces, documentary, artistic, and architectural, that deserve to be investigated with increasing quantitative rigor and systematic comparison and integration with findings from scientific disciplines.

Among such regions is the metropolitan area of Naples, which lies between two active volcanoes: the Campi Flegrei caldera to the west, and Mount Vesuvius, world-renowned for its frequent and often destructive eruptions, to the east (Fig. 1). The location of Mount Vesuvius near Naples urban areas heightens its potential impact during eruptions.

The eruptive history of Vesuvius has been well known since 1631, when a large eruption occurred which inflicted extensive damage to the territory and caused an unspecified number of victims, approximately estimated around 4,000<sup>2,3</sup>. The eruption began on the morning of December 16, with the opening of a fracture on the southwestern flank of the volcano, followed by the formation of an eruptive column 17–21 km high and the fallout of ash and lapilli in the eastern and northeastern sectors of the volcano<sup>4</sup>. On the following day, December

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**Fig. 1.** Map of the Neapolitan volcanic area (the base satellite image was acquired from Google Earth Pro, acquisition date 10/19/2022, Data SIO, NOAA, U.S. Navy, NGA, GEBCO; Image Landsat / Copernicus; image IBCAO). The volcanic areas of Vesuvius and the Campi Flegrei are highlighted by yellow dashed circles. The area outlined in red indicates the impact zone of the 1631 Vesuvius eruption, reconstructed based on Santacroce et al.<sup>1</sup>. The red arrow marks the location of Monte Nuovo, the site of the most recent eruption of the Campi Flegrei.

17, a column collapse generated pyroclastic flows from the central crater that reached the sea, significantly advancing the coastline and devastating the villages at the foot of Vesuvius. The eruptive phenomena were accompanied by rainstorms and the occurrence of destructive mudflows and lahars in the valleys of the volcano and in the northern and northeastern plains<sup>4</sup>. In total, the eruption ejected approximately between 0.07–0.21 cubic kilometers of juvenile volcanic material<sup>4</sup>. This eruption was preceded by many seismic and volcanic precursors. The precursors are described in a book by Braccini<sup>5</sup> and reported in a marble plaque still visible in Portici founded after the eruptive event (Fig. S1). Cesare Braccini in his book “Dell’Incendio fattosi al Vesuvio a’ XVI Dicembre 1631, e delle sue causa ed effetti”<sup>5</sup> reports that several months before the eruption earthquakes were felt in the Vesuvian area. In the same work, Braccini also recalls an excursion to Vesuvius in 1612, during which he noted that a little smoke was coming out of the crater (“usciva un poco di fumo”). The Latin inscription, placed in Portici by the Spanish Viceroy, intended as a solemn reminder and warning to future generations, clearly describes phenomena preceding and accompanying volcanic activity (Fig. S1).

This historical document warns that Mount Vesuvius has erupted numerous times throughout history, often causing devastating loss of life, particularly among those who delayed evacuation. However, volcanic eruptions at Vesuvius are typically preceded by a range of observable precursory phenomena, including seismic swarms, ground deformation, explosions, and persistent tremors. For this reason, it is essential that individuals residing in the vicinity of the volcano evacuate promptly at the onset of such warning signs. Historical accounts demonstrate that delayed responses to these precursors have resulted in significant casualties (see Sect. 1 in Supplementary Information).

This catastrophic eruption marked a turning point in both public awareness and governmental attitudes towards volcanic hazards. Prior to this event, knowledge regarding the volcanic risk posed by Vesuvius was likely underestimated or even neglected by local governance. The 1631 eruption definitely altered this perception. The governing authorities became considerably more aware of the volcanic hazards associated with Vesuvius, shifting their approach towards a strategy focused on mitigating and adapting to the inherent risk rather than ignoring it. Historical documentation and contemporary accounts from this period clearly highlight this shift in governance and public attitude, recognizing the need for coexisting with the volcano and its associated risks.

Consequently, the post-1631 eruptive activity of Mount Vesuvius is exceptionally well documented<sup>6–10</sup> and extensively studied (e.g.<sup>11–17</sup>; see Sect. 7 in Supplementary Information). Observations and monitoring have become progressively more systematic, particularly following the founding of the Osservatorio Vesuviano in 1841. The creation of this observatory marked a significant step forward, institutionalizing volcanic surveillance and scientific research at Vesuvius, which enabled the detailed documentation of volcanic activity since the second half of the 19th century.

In contrast, the documentation of Vesuvius’ activity before the 1631 eruption is incomplete and fragmented. Current reconstructions of its eruptive history suggest that the volcano remained quiescent for an extended

period from 1139 to 1631<sup>14,18</sup>. This prolonged dormancy suggested that the high explosivity of the 1631 eruption, which had a Volcanic Explosivity Index (VEI) of 4–5, was linked with the slow accumulation of magma at shallow depth<sup>19</sup>. Santacroce<sup>19</sup> suggested a direct relationship between repose time and erupted volume, based on a model in which the magma chamber refills at a constant rate. Under the assumption that the entire magma chamber is emptied during major eruptions, the model led to the concept of the ‘Maximum Expected Event’ (MEE) for Vesuvius<sup>20,21</sup>, which has been used to estimate the potential impact of future eruptions in the Vesuvius area. However, further studies<sup>22</sup> have shown that complete emptying of a magma chamber during an eruption is a very rare event, typically associated with catastrophic caldera collapse<sup>23</sup>.

Several volcanological studies have addressed the classification and reconstruction of the eruptive history of Mt. Vesuvius, leading to the development of a dataset of Vesuvius eruptions (e.g.<sup>14,15,18–20</sup>). For the reconstruction of the eruptive history of Vesuvius from a strictly volcanological perspective, we refer directly to this body of literature and its cited references. Within this framework, repose time can be defined as the interval between two consecutive eruptions for which ages could be determined. However, as is well known, reconstructing the complete eruptive record of a volcano is challenging when relying solely on the preserved deposits of past eruptive events, as such deposits are often reworked or eroded, and in most cases only those from the largest eruptions are reliably preserved. Moreover, in general, defining whether an occurrence represents a single event or part of a sequence culminating in a larger eruption is not always straightforward or unambiguous.

Addressing this issue in detail is beyond the scope of this work; however, the case of Vesuvius clearly demonstrates that integrating a strictly volcanological approach with insights from historical, artistic, and literary disciplines, together with the recovery of direct observational reports, enables a more complete reconstruction of the eruptive history and a deeper understanding of volcanic behavior. A clear example is the detailed eruptive record available for the post-1631 period, which exists thanks to the abundance of documentary sources (see “Historical Catalogue of Vesuvius Eruptions (1631–1944),” Sect. 7 in the Supplementary Information).

The case of Vesuvius also illustrates the importance of considering activity reports and studies from earlier scientific literature, such as those by Giovanni Battista Alfano<sup>24</sup>, which will be discussed in detail below. Historical records report volcanic activity between 1306 and 1568; however, these accounts have generally been considered unreliable. In the following sections, we will examine literary references and, in light of recent restorations, further investigate selected artistic evidence indicating that Mount Vesuvius was not entirely inactive during the 16th century.

## Results

### Review of previous volcanological studies

Professor Giovanni Battista Alfano, who became director of the Seismic Observatory of Pompeii following the 1906 eruption of Mt. Vesuvius, collected accounts and evidence of Vesuvius eruptions from AD 79 to 1631<sup>24</sup>. He opens his work with the following statement: “Among all the chapters in the history of Vesuvius, the one concerning the eruptions between AD 79 and 1631 contains the greatest uncertainties and contradictions. Very few reports are accepted by the majority of the most meticulous Vesuvian scholars; many are not supported by documents; a great number are unfounded or plainly incorrect”. However, in his critical review, in which he reports and comments on all available information regarding Vesuvius activity in the target period of his study, Alfano finds several information that he considered relatively reliable.

This study builds upon this critical analysis of historical sources, which also refers to certain artistic evidence that will be discussed later, by adding new elements and constraints derived from research conducted over the past few decades. The new information that can now be incorporated once again challenges the assumption that Vesuvius was inactive between 1139 and 1631.

One of the first volcanological studies that highlights possible eruptive activity at Vesuvius during this interval is that of Cioni et al.<sup>25</sup>, who studied the fallout deposits and identified six deposits associated with VEI 3 eruptions that occurred between the Pollena eruption of AD 472 (VEI 4) and the 1631 eruption (VEI 4–5). These deposits were further characterized in greater detail by Cioni et al.<sup>14</sup> and Santacroce et al.<sup>15</sup>, the latter also providing calibrated radiocarbon <sup>14</sup>C ages for some of them. In particular, the deposit labeled AS5 is associated with calibrated <sup>14</sup>C ages of 580 ± 50 and 520 ± 40 years BP<sup>14,15</sup>, and the calibrated <sup>14</sup>C ages for the 1631 eruption deposits are 520 ± 40 and 410 ± 70 years BP<sup>13–15,26</sup>. To better compare the ages of the AS5 deposit and the 1631 eruption, we calculated the mean calibrated <sup>14</sup>C age for the 1631 event, which resulted in AD 1484, and the mean calibrated <sup>14</sup>C age for the AS5 deposit, which resulted in AD 1400. This indicates a difference of 84 years between the two calibrated mean ages. Since the historical date of the 1631 eruption is well established, subtracting this difference from 1631 allows us to estimate a possible historical age for the AS5 eruption. This yields an approximate date of AD 1547 (± 55 years based on the average of the uncertainties).

Independently, based on a historical approach, Guidoboni and Boschi<sup>27</sup> report the discovery of a previously unknown historical source, a manuscript dated 1571 by Pirro Ligorio, preserved in the State Archives of Turin. The document contains a detailed eyewitness account of volcanic activity at Mount Vesuvius, including persistent fumaroles, daytime smoke, nighttime flames, minor explosions, and the emission of pumice. These observations point to eruptive phenomena occurring around 1570.

Dating to roughly the same period is the 1562 inscription from Torre del Greco, which reports damage to the road between Naples and Reggio caused by stones ejected from Vesuvius (see Sect. 2 in Supplementary Information and Fig. S2), later repaired by order of Viceroy Pedro Afan de Ribera, Duke of Alcalá, using provincial funds (Fig. 2). This inscription was recently re-examined by Giacomelli et al.<sup>28</sup>, who highlighted its significance for understanding Vesuvius activity during that period.



**Fig. 2.** Torre del Greco inscription, 1562. "The road from Naples to Reggio, once made treacherous by constant acts of brigandage and blocked by rocks thrown up by the eruption of Vesuvius, was built wide and straight, with provincial funds, by Pedro Afan de Ribera, Duke of Alcala, viceroy, after the area had been cleared of dangers and the surface leveled. In the year 1562" (see Sect. 2 in Supplementary Information and Fig S2).

### Artistic and literary information

#### *The fresco in the church of San Gennaro dei poveri (1525–1530)*

The main piece of artistic evidence for Vesuvius activity in the sixteenth century is the fresco in the Church of San Gennaro dei Poveri in Naples, depicting the Saint protecting the city from a Vesuvius eruption. This fresco, already mentioned by Alfano<sup>24</sup> and other scholars (e.g.<sup>29–31</sup>), is located in the entrance hall of the church. The elements that emerged from studies related to the recent restoration (2014–2015) of the fresco cycle, curated by Prof. Leone de Castris<sup>32</sup>, allow for the reconstruction of its attribution to Andrea Sabatini and other artists from his workshop, a precise dating, as well as an appropriate interpretation of the testimonial significance of the fresco of San Gennaro (Saint Januarius) and Vesuvius, based on historical-artistic analysis and the intended message of the work.

The formal characteristics of the cycle to which the fresco of San Gennaro and Vesuvius belongs, and comparisons with other signed, dated, or documented works by Andrea Sabatini from the 1520s, confirm that the fresco was conceived and partially executed by the master with the collaboration of his workshop, including artists such as Polidoro da Caravaggio, Agostino Tesauro, and possibly Giovan Filippo Criscuolo. The work was executed between 1525 and 1530.

The fresco portrays a volcanic eruption of Vesuvius with a high degree of realism and fidelity, consistent with the Renaissance revival of classical naturalism and realism. The historical-artistic analysis indicates that the depiction does not appear to be the work of someone unfamiliar with such an event or uninspired by direct witnesses or visual records of an eruption. It cannot be a copy of medieval examples, which would have featured a strongly symbolic and non-realistic style, markedly different from the Renaissance approach. For this reason, the fresco holds significant testimonial value. Moreover, the aim of the fresco is both to foster devotion to the Saint and to preserve the memory and identity of the community by recalling an important event, an eruption of Vesuvius that, thanks to the protection of San Gennaro, did not cause damage to the city. This contributed to the creation of a shared identity and reinforced the community's sense of belonging (see Sect. 3 in Supplementary Information and Fig. S3).

The erupting Vesuvius depicted in the fresco bears a notable resemblance to scientific illustrations, such as those published in Luigi Palmieri's 1880 book "Il Vesuvio e la sua storia"<sup>33</sup>, which depicts the 1794 eruption.

Figure 3 shows the fresco from the Church of San Gennaro dei Poveri displayed alongside the aforementioned illustration from Palmieri's book<sup>33</sup>.

#### *The contract between the City of Naples and Saint Januarius (1527)*

We owe the valuable pictorial testimony of Vesuvius erupting in the 16th century (Fig. 3) to the strong cultural and religious connection between the volcano and Saint Januarius (San Gennaro), the Christian martyr beheaded in AD 305 inside the crater of the Solfatara.

According to deeply rooted Neapolitan tradition, Saint Januarius protects the city from Vesuvian eruptions. From this same period (1527) dates the official contract established between the city of Naples and Saint Januarius. Some excerpts from this document read:

In the year of Our Lord 1527, on January 13, on the feast day of the translation of the most glorious pontiff and martyr Januarius to the interior of the Major Church of Naples, in the presence of myself, Notary, and of six noble representatives (the noble councils of Capuano, Nilo, Montanea, Portanova, Porto, and the Elected Nobles of the city of Neapolis), together with a great number of nobles and citizens [...] before the relics of the most glorious pontiff and martyr, namely, the head and the pure blood, and of the people themselves, who processed around the church, joined by some of the Reverend Canons, carrying torches in weekly rotation, solemnly and devoutly circled the church with that multitude of nobles and people, and coming to the high altar, laid down the said relic. While the relic was being venerated, the same holy priest and martyr, chosen by God, was invoked with fervent devotion by the Father, the faithful, and the Holy Spirit [...] so that God may be pleased to protect this city from calamities, diseases, epidemics, and plagues, and restore it to its original state....

This “contract” between the people of Naples and their Patron Saint represents a unique historical event. Two aspects are particularly relevant to the volcanic context:

- 1) The contract was established during the volcanic crisis of the Campi Flegrei<sup>34</sup>, characterized by strong earthquakes, also felt in Naples<sup>35</sup>, ground uplift, and significant fumarolic activity. During the same period, as illustrated in the fresco by Andrea Sabatini, Vesuvius was also exhibiting moderate eruptive activity.
- 2) Saint Januarius, who was martyred in the crater of the Solfatara of Pozzuoli, has long been venerated as a protector against Vesuvian eruptions. Notably, he was invoked during the violent 472 AD eruption of Vesuvius (the Pollena eruption), and from that time onward, he came to be regarded as the official Patron Saint of the city.

This underscores a possible connection between the contract with Saint Januarius and the fear of Vesuvius eruptions during the early sixteenth century. At that time, not only the common people, but also the nobility and the clergy, who governed the city through a system of noble councils, felt the need for the Saint's protection and collectively formalized a pact with Saint Januarius against future calamities.

It is important to consider that in those times, the population, poor, oppressed, and exploited, was difficult to govern and, in the face of fear, could react irrationally, giving vent to long-repressed discontent (see Sect. 4 in Supplementary Information). This initiative thus contributed to the creation of a shared civic identity, reinforced the sense of community belonging, and strengthened the people's loyalty to the Church.

#### *The eruption of Monte Nuovo in Campi Flegrei (1538)*

These were the years leading up to the eruption of Monte Nuovo occurred between September 29 and October 6, 1538, within the Campi Flegrei caldera. In the period preceding that eruption, significant ground deformation, intense gas emissions, and numerous earthquakes were occurring in the nearby Campi Flegrei volcano, often felt in Naples. The unrest that preceded the eruption of Monte Nuovo was long-lasting. The first signs of ground uplift began in the early 15th century. In the following decades, the deformation and the seismicity gradually accelerated. During the final two years prior to the eruptive event, uplift increased by more than eight meters and was accompanied by earthquakes of considerable intensity<sup>34,35</sup>. Seismic and fumarolic activity within the Campi Flegrei caldera persisted for several decades after the Monte Nuovo eruption<sup>35</sup>.

#### *Bernardino Daniello's letter (1539)*

An interesting document related to volcanic activity in the Neapolitan area during this period is a letter by Bernardino Daniello, a Renaissance Italian scholar known for his works on Dante, Petrarch, and Virgil<sup>36</sup>. The letter, addressed to Alessandro Corvino, was written on March 22, 1539, approximately five months after the eruption of Monte Nuovo in the Campi Flegrei. This letter contains, for the first time, the famous expression “A Paradise inhabited by Devils.” The phrase, later adopted by Goethe and Benedetto Croce in reference to the people of Naples, is clearly, when reading the full text of the letter and considering the eruptive history of the Neapolitan volcanoes, a reference by Daniello to the Neapolitan volcanoes themselves.

Indeed, following the Monte Nuovo eruption and in the years thereafter, volcanic phenomena continued, accompanied by numerous earthquakes, felt even in Naples<sup>35</sup>. If we also consider that Vesuvius was not in a state of full quiescence but exhibited intermittent activity, likely phreatic, possibly even Strombolian, with nocturnal glow and ballistic ejections, it becomes evident that the “Devils” Daniello refers to are the volcanoes of the Neapolitan area.

It is worth noting that Daniello's letter praises Naples and never speaks negatively of its inhabitants; on the contrary, he highlights the city's distinguished aristocracy. Furthermore, in 1539, Bernardino Daniello stayed in Naples as a guest of Francesco Cenami, a wealthy merchant and patron of the arts. This circumstance further



**Fig. 3.** Comparison between a sixteenth-century fresco depicting Vesuvius erupting and an illustration of the 1794 Vesuvius eruption. **(a)** The fresco in the Church of San Gennaro dei Poveri in Naples, executed by the Renaissance painter Andrea Sabatini between 1525 and 1530, depicting Saint Gennaro protecting Naples from the eruption of Vesuvius. **(b)** The graphical reproduction of the 1794 eruption of Vesuvius, reported in the Luigi Palmieri's book "Il Vesuvio e la sua storia" (Fig. 8 in Palmieri<sup>33</sup>).

reinforces the conclusion that he had no reason to express himself in negative terms regarding the people of Naples, not least out of consideration for his host.

In the letter written by Bernardino Daniello (see Sect. 5 Supplementary Information, Fig. S4) a few months after the Monte Nuovo eruption, it is not explicitly clear which volcano he refers to, or whether he refers to both Neapolitan volcanoes. However, since Daniello was staying in Naples, whether he directly experienced or observed volcanic phenomena such as earthquakes, explosions, or intense degassing, or whether he simply captured the general atmosphere of public concern, the assumptions from which his reflections originated were rooted in the city of Naples, whose skyline faces Vesuvius, not the Campi Flegrei caldera. It is therefore likely that Bernardino Daniello was referring also, or perhaps primarily, to Vesuvius, which was perceived as actively threatening during that period.

#### *The Spinacorona fountain (1540)*

The Spinacorona Fountain (Fig. 4) is a fountain located in the historic center of Naples. Also known as the “Fountain of the Breasts” (Fontana delle Zizze), it features a particularly striking decoration. The sculpture depicts a siren who, with milk flowing from her breasts, extinguishes the fire of a Vesuvius eruption, represented by curls of lava streaming down the sides of the volcano. On the fountain appeared the Latin inscription “Dum Vesevi Syrena Incendia Mulcet”, which may be rendered as “While the Siren soothes the fires of Vesuvius”. Some decorative details of this fountain (see Sect. 6 Supplementary Information, Fig. S5) could be interpreted as various phenomena, such as lava flows (or mudflows?) or even pyroclastic currents. However, the water spurting from the siren’s breasts, symbolizing her milk, clearly conveys the idea of extinguishing something burning. Therefore, we lean toward interpreting the depicted processes as representations of eruptive phenomena.

As is well known, the siren Parthenope is a symbol of the city of Naples. Around this mythological figure developed the founding legend of the city, whose community is said to have formed around the lifeless body of the siren Parthenope.

The Spinacorona Fountain was restored by Don Pedro de Toledo, the Spanish viceroy, who in 1540 added his coat of arms alongside that of Charles V (the sculptor Giovanni da Nola, a leading figure of the Neapolitan Renaissance, was likely responsible for the restoration). Thus, in 1540, alongside the Christian cult of Saint Januarius, an older and more pagan cult reemerges: that of the siren, who with her body protects Naples, the city she is said to have given birth to, from the eruption of Vesuvius.



**Fig. 4.** The Spinacorona Fountain, depicting a siren quelling a Vesuvius eruption with milk flowing from her breasts. The fountain was restored in 1540.

It is interesting to note that, in the same years, in another overseas Spanish viceroyalty, Guatemala, and in particular the city of La Antigua, the symbol of the siren also spread. This city was threatened by two major volcanoes: Volcán de Agua and Volcán de Fuego, the latter being one of the most active and hazardous volcanoes in the world. We propose a speculative hypothesis of a possible historical link between the two Spanish viceroyalties, which, during the same historical period, were both facing comparable volcanic threats. This shared experience may have contributed to the introduction of the siren as a protective symbol against volcanic phenomena in the overseas viceroyalty as well. The myth of the siren in Guatemala remains enigmatic and is not yet fully understood by local art historians. This interpretative hypothesis may serve as a stimulus for further research in the fields of art history and the humanities.

*“View of the Port of Naples” painting by Pieter Bruegel (1556) and Vesuvius from an engraving by Georg Hoefnagel (1578)*

The painting *View of the Port of Naples* by Pieter Bruegel is datable to around 1556 and is held at the Galleria Doria Pamphilj in Rome. It was painted after the artist’s return from a trip to Italy and Naples (Fig. 5). The work depicts the port of Naples seen from the sea, crowded with ships and boats, with Mount Vesuvius in the background on the right, showing summit glow and a reddish plume. The painting has been interpreted by several authors [e.g.<sup>31</sup> ] as further evidence of summit activity at Vesuvius during Bruegel’s journey to Italy, which brought him to Naples by sea. However, this artistic testimony is not unanimously recognized as proof of volcanic activity at Vesuvius, since the area where the flashing hues are visible corresponds to the sunrise over the Gulf of Naples. Therefore, the glow could be attributed to dawn.

A few years later (1578), the engraving by Georg Hoefnagel depicts Vesuvius with a plume-like feature (Fig. 6). This image has been interpreted as further evidence of degassing activity from the summit crater<sup>31</sup>. Degassing does not necessarily imply eruptive activity, but in a closed-conduit volcano, such as Vesuvius is currently considered to be, a well-developed fumarolic plume is unlikely. Therefore, intense degassing capable of generating a visible plume at the summit of Vesuvius still represents a volcanic manifestation that deserves to be taken into account.

### Summary of results

By combining the information reported in Alfano<sup>24</sup> with findings from more recent scientific studies<sup>27</sup>, as well as the historical and artistic evidence discussed above<sup>31,32</sup>, we can identify reliable indications of Vesuvius activity



**Fig. 5.** View of the Port of Naples by Pieter Bruegel (1556). Vesuvius is visible on the right, with summit glow.



**Fig. 6.** The engraving by Georg Hoefnagel (1578) likely depicts signs of degassing at Vesuvius.

between 1139 and 1631. The information is presented in the following numbered list, which includes the date, a description of the account, and the source in which it was reported:

- (1) - 1150 AD. Vesuvius continuously emitted fire and stones (El Eldrisi)<sup>24</sup>.
- (2) - 1270 AD. Thomas Aquinas, commenting on Boethius' *De consolazione philosophiae*, wrote that Vesuvius was always burning<sup>24</sup>.
- (3) - 1347 AD. Petrarca stated that Vesuvius "used to erupt flames"<sup>24</sup>.
- (4) - 1353 AD. Boccaccio noted that in his time, Vesuvius emitted neither smoke nor fire<sup>24</sup>.
- (5) - 1360 AD. Fazio degli Uberti wrote that the volcano emitted lights<sup>24</sup>.
- (6) - 1410 AD. According to the <sup>14</sup>C dating of the AS5 deposit by Cioni et al.<sup>14</sup> and the subsequent calibration published in Santacroce et al.<sup>15</sup>, this deposit dates to AD 1400. However, based on our considerations outlined above, aimed at estimating the age difference between this deposit and that of the 1631 eruption (using the calibrated radiocarbon ages of both deposits reported in Santacroce et al.<sup>15</sup>), it could speculatively be attributed to a period around the mid-16th century (AD 1547 ± 55 years), with an uncertainty of approximately half a century<sup>15</sup>.
- (7) - 1430 AD -1440 AD. Limited documentation is available for the entire 15th century. Only one report refers to activity around 1430 (Sorrentino states that volcanic activity occurred 70 years before the 1500 eruption reported by Ambrogio da Nola). In addition, some sources mention an eruption in 1440, citing as supporting evidence a decree issued in that year by the Archbishop of Naples, Gaspare da Diano, establishing a special cult in honour of Saint Januarius, the city's patron Saint. Finally, the abbot Pompeo Sarnelli, in his "Guida de' forestieri curiosi di vedere e d'intendere le cose più notabili della regal città di Napoli e del suo amenissimo distretto", published in 1687, also reports an eruption in 1430<sup>24,37</sup>.
- (8) - 1500 AD. Ambrogio Leone reported an eruption of Vesuvius, though it likely refers to an ash eruption<sup>24,38</sup>.
- (9) - 1501 AD. de Oviedo Valdes Gonzalo, a Spanish visitor, climbed to the crater and observed smoke emissions; he also reported accounts of visible fire at night<sup>24</sup>.
- (10) - 1525 – 30 AD. The fresco in the Church of San Gennaro dei Poveri depicting Vesuvius in eruption with realistic detail<sup>31,32</sup>] (Figs 3 and S3).
- (11) - 1527 AD. The contract between the city of Naples and Saint Januarius.
- (12) - 1539 AD. Bernardino Daniello's letter.
- (13) - 1540 AD. The Spinacorona Fountain<sup>24</sup> (Fig. 4).
- (14) - 1545 AD. Giorgio Agricola wrote that Vesuvius was emitting smoke in some areas<sup>24</sup>.
- (15) - 1550 AD. Alberti stated that the volcano no longer produced fire<sup>24</sup>.

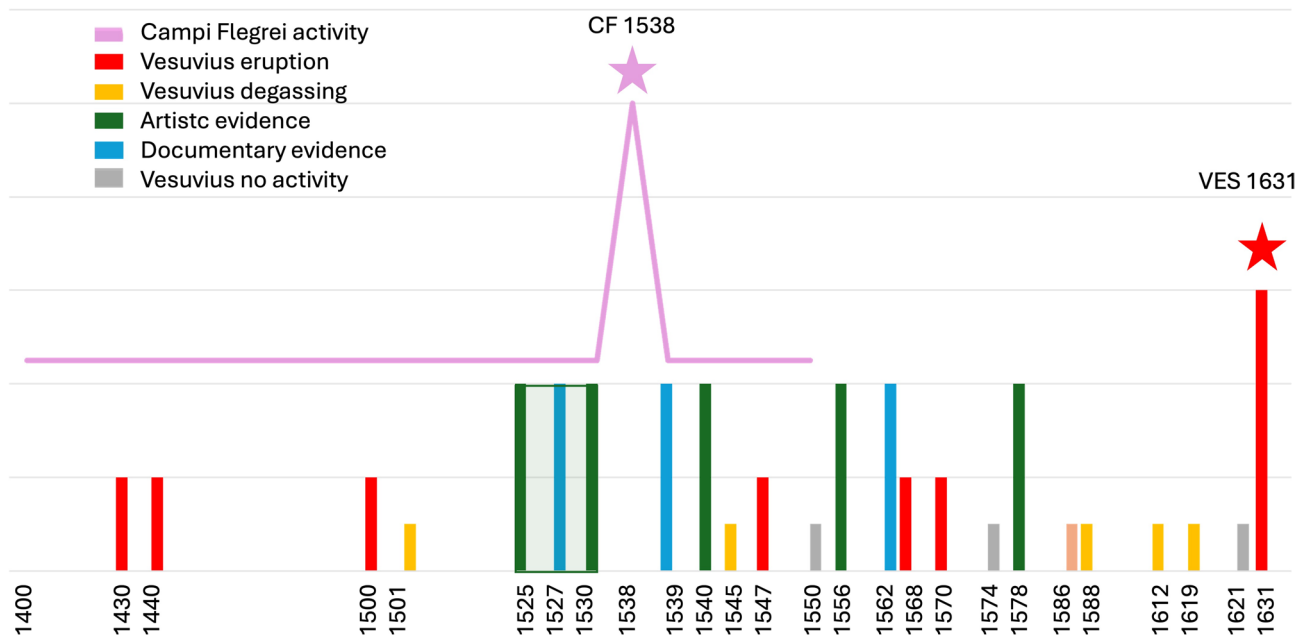


Fig. 7. Plot of summary of results (“Summary of results”), starting from the year 1400.

(16) - 1556 AD. View of the Port of Naples painting by Pieter Bruegel<sup>31</sup> (Fig. 5).

(17) - 1562 AD. Torre del Greco inscription. The road from Naples to Reggio, once made treacherous by constant acts of brigandage and blocked by rocks thrown up by the eruption of Vesuvius, was built wide and straight, with provincial funds, by Pedro Afan de Ribera, Duke of Alcala, viceroy, after the area had been cleared of dangers and the surface leveled. In the year 1562<sup>28</sup> (Fig. 2).

(18) - 1568 AD. According to Daniele Barbaro, an eruption has occurred<sup>24</sup>.

(19) - 1570 AD. According to Pirro Ligorio an eruption has occurred<sup>27</sup>.

(20) - 1574 AD. Pighio found the crater completely inactive<sup>24</sup>.

(21) - 1578 AD. The engraving by Georg Hoefnagel (1578) likely depicts signs of degassing at Vesuvius<sup>31</sup>.

(22) - 1586 AD. Scipione Mazzella confirmed that Vesuvius had once emitted sparks<sup>24</sup>.

(23) - 1588 AD. People used the volcanic cavities on Vesuvius as natural steam baths<sup>24</sup>.

(24) - 1612 AD. Braccini visited the volcano and found it inactive<sup>24</sup>, although it was emitting smoke<sup>5</sup>.

(25) - 1619 AD. Magliocco reported small pools of warm water at the bottom of the crater<sup>24</sup>.

(26) - 1621 AD. Doglioni wrote that Vesuvius was inactive<sup>24</sup>.

(27) - 1631 AD. Ten years later, the devastating eruption of 16 December 1631 occurred<sup>5</sup>.

The numerous indications of possible volcanic activity at Vesuvius reported above fall within the long quiescent interval identified by strictly volcanological studies (e.g. <sup>14,15,18-20</sup>), which preceded the 1631 eruption. This suggests that the actual duration of the repose period prior to that eruption may have been considerably shorter. However, precisely defining whether a given occurrence represents an independent eruption or rather part of a sequence culminating in a larger event is not unambiguous, and lies beyond the scope of this work.

## Discussion

We have summarized the information listed in “Summary of results”, starting from the year 1400, in the chart presented in Fig. 7. This figure presents the period of activity of the Campi Flegrei caldera (pink line), based on previous studies<sup>34,35</sup>, with the eruption of Monte Nuovo marked by a pink star. In addition, Vesuvius eruptions (red bars) are reported based on the list presented above (“Summary of results”). The event attributed to 1547 is the one dated by Cioni et al.<sup>14</sup> and calibrated by Santacroce et al.<sup>15</sup>, which, according to the reasoning discussed in “Review of previous volcanological studies”, we tentatively assign to the year 1547 (+/- 55 years). The red star indicates the 1631 eruption. Also plotted are observations of smoke, sparks, and the use of caves as thermal baths at Vesuvius, interpreted as signs of activity (yellow bars). Some entries refer to the absence of volcanic activity and are represented by grey bars.

The summary plot includes artistic evidence (green bars) and indirect documentary sources, such as the “contract” of Naples with San Gennaro, Bernardino Daniello’s letter, and the 1562 inscription from Torre del Greco. The green transparent rectangle between 1525 and 1530 highlights the time window of attribution for the fresco of San Gennaro and Vesuvius, corresponding to point 10 in the list of “Summary of results”.

This chart reveals an interesting concentration of artistic and documentary evidence related to Vesuvius during the period of most intense unrest at Campi Flegrei, which ultimately culminated in the 1538 Monte Nuovo eruption. This suggests that volcanic activity at Vesuvius was indeed occurring, as evidenced by the fresco of Saint Januarius and Vesuvius. However, the perception of the phenomena during that period overlapped with those resulting from the unrest at the Campi Flegrei, such as the experience of earthquakes.

It is also noteworthy that, beginning around 1550, references to the absence of volcanic activity at Vesuvius begin to appear, an aspect we consider meaningful. Apparently, the lack of eruptive phenomena at that time was not taken for granted, rather, it represented a notable condition of stasis. For example, if one were to climb Vesuvius today, they would not record the absence of eruptive activity in a notebook, as such absence is expected during a known phase of quiescence.

Among the various accounts of 16th-century volcanic activity of Vesuvius, the most compelling evidence is the fresco by Andrea Sabatini (point 10 of the previous list), which could not have been painted without either direct observation of an eruption or access to a near-contemporary visual representation. This significant artistic source lends renewed strength to other historical reports, contributing to a more coherent framework that links the eruptive histories of Vesuvius and Campi Flegrei caldera over the long term. Notably, during the same decades in which Vesuvius showed signs of moderate activity, including major eruptions such as the event depicted in the fresco in the Church of San Gennaro dei Poveri, the Campi Flegrei underwent a prolonged phase of unrest culminating in the 1538 eruption, the Monte Nuovo eruption. Seismicity and possibly ground deformation persisted in the Campi Flegrei caldera for several years thereafter<sup>35</sup>. Thus, it is evident that the phenomena perceived by the people of Naples affected not only the Campi Flegrei area but also the Vesuvius region, as suggested by the evidence summarized above (from point 8 to point 25 of the list). The perception of these phenomena, widespread across the two volcanic areas west and east of Naples, may have inspired Bernardino Daniello to liken Naples to Laura, Petrarch's muse, whose beauty doomed her to a short life. Similarly, Naples, a terrestrial paradise, was "given to the devils to inhabit", a reference to its volcanoes.

Improved understanding of the poorly documented activity of Vesuvius during the sixteenth century, an era that coincides with the onset of Spanish viceroyalty, and the reconstruction of volcanic events affecting both the Vesuvius and Campi Flegrei areas, located respectively to the east and west of Naples, have significant implications for the assessment of the behavior of the Neapolitan volcanic region.

First, the results of our study allow us to reconstruct the volcanic events that affected the Vesuvius and Campi Flegrei areas, and to outline a long-term evolutionary scenario in which the two volcanic systems appear to be more closely linked than previously assumed. Indeed, the sequence of events began with a prolonged phase of unrest at Campi Flegrei, which eventually culminated in the modest eruption of Monte Nuovo in 1538. Simultaneously with these events occurring at Campi Flegrei, Vesuvius began to exhibit signs of reawakening. In this regard, it is worth noting that the eruption depicted by Andrea Sabatini in the fresco at San Gennaro dei Poveri must have occurred before 1525–1530 (the time range to which the painting is dated) and therefore predates the Monte Nuovo eruption. Finally, this long-term evolutionary scenario culminated in the major eruption of Vesuvius in 1631. A sort of relationship between the Vesuvius and Campi Flegrei in their current state has also been hypothesized in some recent studies using different approaches<sup>16,17,39,40</sup>.

Moreover, a widely held paradigm in volcanology suggests that the magnitude of the eruption tends to increase with the preceding repose period. Very large eruptions ( $VEI \geq 4-5$ ) are often preceded by centuries or even millennia of dormancy, reflecting the time required for magma reservoirs to evolve and accumulate enough volatiles to sustain explosive activity. Processes such as crystal fractionation, crustal assimilation, and magma mixing are inherently slow and are thought to play a key role in lengthening repose intervals before major eruptions. However, growing observational and historical evidence challenges this simplistic view.

There are numerous historical examples of large explosive eruptions that occurred after surprisingly short repose periods, undermining the assumed direct correlation between eruption size and dormancy duration. For instance, Mount St. Helens (Washington state) experienced two VEI 5 eruptions in close succession in the late 15th century, separated by only two years, as part of a cluster of Plinian events within a short time span. Similarly, volcanoes such as in Philippine, Taal 1754 and Mayon 1814 and 1987, or in Japan Asama 1783, have produced major eruptions just a few decades, or even years, after previous activity, indicating that recharge and pressurization of the magma system can proceed rapidly under favorable conditions. In the case of Quizapu in Chile, a large VEI 5 silicic eruption in 1932 was preceded by nearly a decade of phreatic and mafic eruptions, demonstrating how prolonged low-level activity can culminate in a major event. More recent examples, such as the 2015 eruption of Calbuco in Chile (VEI 4) or the 2022 Hunga Tonga–Hunga Ha'apai VEI 5–6 eruption occurred after decades of minor activity, further illustrate how large eruptions can emerge from relatively short repose intervals. These cases emphasize that while the general trend linking longer repose with larger eruptions holds in many systems, it is by no means universal. Volcanic systems are complex and modulated by a wide range of factors, including magma supply rates, conduit openness, and the physical state of the reservoir, that can override the expected timescales of magmatic evolution. As such, reliance on repose duration alone as an indicator of eruption size can be misleading and must be integrated with real-time monitoring and contextual geological understanding.

Within this framework, the present study provides new insights that may contribute to a better understanding of the possible long-term evolution of the current state of the Neapolitan volcanic systems. This, in turn, may support the formulation of realistic future scenarios, with potentially positive implications for volcanic risk management in the Vesuvius area and the Neapolitan volcanic region more broadly.

## Methods

The approach adopted in this study is highly interdisciplinary, integrating methods from historical volcanology and art-historical analysis. The historical literature (e.g. <sup>5</sup>), and major reviews of Vesuvius-related sources<sup>24,28,29,31,41–44</sup> were re-examined. Artistic and literary testimonies were also reassessed<sup>32,35</sup> in light of recent advances in the interpretation of artworks and historical references cited in this study. In particular, the in-depth study of the fresco by Andrea Sabatini and its precise dating (1525–1530)<sup>32</sup> demonstrate that Vesuvius produced a typically 'Vesuvian' eruption prior to 1530, thus, before the Monte Nuovo eruption, while the Campi Flegrei were undergoing their well-documented long-term unrest, as reported in numerous sources<sup>34</sup>. The

primary methodological effort of this study consisted in integrating knowledge from different disciplinary fields and fostering a constructive dialogue among them.

## Data availability

All data generated or analysed during this study are included in this published article.

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## References

- Santacroce, R. et al. *Carta Geologica Del Vesuvio Scala 1:15000* (CNR, 2003).
- Alfano, G. B. & Friedlaender, I. *La storia del Vesuvio illustrata dai documenti coevi* (Karl Hohn, Ulm a.d. Donau, Germany, 69 pp., 1929).
- Lirer, L., Petrosino, P., Munno, R. & Grimaldi, M. *Vesuvius Through History and Science* (Electa, 2009).
- Rosi, M., Principe, C. & Vecchi, R. The 1631 Vesuvius eruption: A reconstruction based on historical and stratigraphical data. *J. Volcanol Geotherm. Res.* **58**, 151–182 (1993).
- Braccini, G. C. *Dell'incendio Fattosi Al Vesuvio XVI Dicembre 1631, E Delle Sue Cause Ed Effetti* (S. Roncagliolo, 1632).
- Scandone, R. & Giacomelli, L. The slow boiling of magma chambers and the dynamics of explosive eruptions. *J. Volcanol Geotherm. Res.* **110**, 121–136 (2001).
- Giudicepietro, F. et al. Seismological monitoring of Mount Vesuvius (Italy): more than a century of observations. *Seismol. Res. Lett.* **81**, 625–634 (2010).
- Cubellis, E., Marturano, A. & Pappalardo, L. Le ceneri distali Dell'eruzione Del vesuvio Del Marzo 1944 raccolte a Devoli (Albania). *Quad. Geofis.* **113**, 1–35 (2013). <https://istituto.ingv.it/images/collane-editoriali/quaderni-di-geofisica/quaderni-di-geofisica-2013/quaderno113.pdf>
- Cubellis, E., Marturano, A. & Pappalardo, L. The last Vesuvius eruption in March 1944: reconstruction of the eruptive dynamic and its impact on the environment and people through witness reports and volcanological evidence. *Nat. Hazards.* **82**, 95–121 (2016).
- Scandone, R. *Vesuvio Storie Di Uomini E Eruzioni* (Independently published, 2022).
- Scandone, R., Giacomelli, L. & Gasparini, P. Mount Vesuvius: 2000 years of volcanological observations. *J. Volcanol Geotherm. Res.* **58**, 5–25 (1993).
- Scandone, R. & Giacomelli, L. Precursors of eruptions at Vesuvius (Italy). *J. Volcanol Geotherm. Res.* **171**, 191–200 (2008).
- Santacroce, R. (ed) *Somma-Vesuvius*, vol. 114 of *Quaderni di La Ricerca Scientifica* (Consiglio Nazionale delle Ricerche, Roma, 230 pp., 1987).
- Cioni, R., Bertagnini, A., Santacroce, R. & Andronico, D. Explosive activity and eruption scenarios at Somma-Vesuvius (Italy): towards a new classification scheme. *J. Volcanol Geotherm. Res.* **178**, 331–346 (2008).
- Santacroce, R. et al. Age and whole rock-glass compositions of proximal pyroclastics from the major explosive eruptions of Somma-Vesuvius: A review as a tool for distal tephrostratigraphy. *J. Volcanol Geotherm. Res.* **107**, 1–18 (2008).
- Pappalardo, L. & Mastrolorenzo, G. Rapid differentiation in a sill-like magma reservoir: A case study from the Campi Flegrei caldera. *Sci. Rep.* **2**, 712 (2012).
- Giudicepietro, F. et al. Campi Flegrei, Vesuvius and Ischia seismicity in the context of the Neapolitan volcanic area. *Front. Earth Sci.*, **9** (2021).
- Principe, C. et al. Chronology of Vesuvius' activity from A.D. 79 to 1631 based on archaeomagnetism of lavas and historical sources. *Bull. Volcanol.* **66**, 703–724 (2004).
- Santacroce, R. A general model for the behaviour of the Somma Vesuvius volcanic complex. *J. Volcanol Geotherm. Res.* **17**, 237–248 (1983).
- Barberi, F., Macedonio, G., Pareschi, M. T. & Santacroce, R. Mapping the tephra fallout risk: an example from Vesuvius (Italy). *Nature* **344**, 142–144 (1990).
- Macedonio, G., Pareschi, M. T. & Santacroce, R. Renewal of volcanic activity at Vesuvius: tephra fallout. *J. Volcanol Geotherm. Res.* **40**, 327–342 (1990).
- Macedonio, G., Neri, A., Martí, J. & Folch, A. Temporal evolution of flow conditions in sustained magmatic explosive eruptions. *J. Volcanol Geotherm. Res.* **143**, 153–172 (2005).
- Martí, J., Folch, A., Neri, A. & Macedonio, G. Pressure evolution during explosive caldera-forming eruptions. *Earth Planet. Sci. Lett.* **175**, 275–287 (2000).
- Alfano, G. B. *Il Vesuvio E Le Sue Eruzioni* (Scuola Tipografica Pontificia, 1924).
- Cioni, R. et al. Assessing pyroclastic fall hazard through field data and numerical simulations: example from Vesuvius. *J. Geophys. Res. : Sol Ea.* **108**, 2063–2073 (2003).
- Wulf, S., Kraml, M., Brauer, A., Keller, J. & Negendank, J. F. W. Tephrochronology of the 100 ka lacustrine sediment record of Lago Grande Di monticchio (southern Italy). *Quatern Int.* **122**, 7–30 (2004).
- Guidoboni, E. & Boschi, E. Vesuvius before the 1631 eruption. *Eos Trans. Am. Geophys. Union.* **87**, 427–423 (2006).
- Giacomelli, L., Foresta Martin, F. & Scandone, R. *La penisola dei vulcani. L'attività vulcanica in Italia tra ricerca e prevenzione* (Francesco Brioschi Editore, 2022).
- Nazzaro, A. *Il Vesuvio: storia eruttiva e teorie vulcanologiche* (Liguori Editore, 1997).
- Nazzaro, A. Some considerations on the state of Vesuvius in the middle ages and the precursors of the 1631 eruption. *Ann. Geophys-Italy.* **41**, 555–565 (1998). <https://www.earth-prints.org/handle/2122/1468>.
- Ricciardi, G. P. *Diario del Monte Vesuvio*. No.1 in Collana INGV - Vulcanica (ESA - Edizioni Scientifiche e Artistiche, Torre del Greco (NA), Italy, 2009).
- Leone de Castris, P. *Andrea Sabatini da Salerno: il Raffaello di Napoli* (Arte'm, 2017). <https://books.google.it/books?id=XwiWswEACAAJ>.
- Palmieri, L. *Il Vesuvio E La Sua Storia* (Tipografia Faverio, 1880).
- Di Vito, M. A. et al. Magma transfer at Campi Flegrei caldera (Italy) before the 1538 AD eruption. *Sci. Rep.* **6**, 32245 (2016).
- Guidoboni, E. & Ciuccarelli, C. The Campi Flegrei caldera: historical revision and new data on seismic crises, bradyseisms, the Monte Nuovo eruption and ensuing earthquakes (twelfth century 1582 AD). *Bull. Volcanol.* **73**, 655–677 (2011).
- Pirovano, D. *Bernardino Daniello*. In (eds Malato, E. & Mazzucchi, A.) *Censimento Dei Commenti Danteschi - 2. I commenti Di tradizione a Stampa (dal 1477 al 2000) e Altri di Tradizione Manoscritta Posteriori al 1480* (Salerno Editrice, Roma, 2014).
- Sarnelli, P. *Guida de' forestieri curiosi di vedere e d'intendere le cose più notabili della regal città di Napoli e del suo amenissimo distretto* (Roselli, G., Napoli, 1687).
- Leone, A. *De Nola* (Giovanni Rosso di Vercelli, 1514).
- Amoruso, A. & Crescentini, L. DInSAR data reveal an intriguing contemporaneous onset of deep deflation below Vesuvio and the ongoing Campi Flegrei uplift. *Remote Sens.* **15**, 3038 (2023).

40. Amoroso, A., Gualandi, A. & Crescentini, L. On the initial phase of the ongoing unrest at Campi Flegrei and its relation with subsidence at Vesuvio (Italy). *Remote Sens.* **16**, 1717 (2024).
41. Figliuolo, B. & Marturano, A. *Catalogo Delle eruzioni vesuviane in Età medioevale (secoli VII-XV)*. In (ed Luongo, G.) *Mons Vesuvius*, 77–90 (Fiorentino Editore, Napoli, 1997).
42. Figliuolo, B. & Marturano, A. *The eruption of Vesuvius from 7th to the 12th centuries*. In (ed Morello, N.) *Volcanoes and History*, 133–156 (Brigati, Genova, 1998).
43. Lirer, L. *Riflessioni di un Vulcanologo Napoletano* (Independently published, 2020).
44. Luongo, G. & Cubellis, E. *Mons Vesuvius - La montagna di fuoco addormentata* (Bibliopolis, Napoli, 230 pp., 16 Table, 2025).

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## Author contributions

FG: conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; validation; writing original draft; writing, review and editing. PC, CDP, CM: data curation; formal analysis; investigation; methodology; writing original draft. EC, LG, GM, LP, RS, PLdC: conceptualization; data curation; formal analysis; investigation; methodology; validation; writing original draft.

## Declarations

### Competing interests

The authors declare no competing interests.

### Additional information

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