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Received: 7 February 2023 | Revised: 24 May 2023 | Accepted: 9 August 2023

DOI: 10.1111/ter.12678

REVIEW ARTICLE

Terra Nova WILEY

A review of the tectonic, volcanological and hazard history of Vulcano (Aeolian Islands, Italy)

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Funding information
European Commission; Istituto Nazionale di Geofisica e Vulcanologia

Abstract

Vulcano is one of the seven volcanic islands composing the Aeolian Islands archipelago (Southern Italy), which also includes three other active volcanoes. The island was originally a stratovolcano like Stromboli; afterwards, its shape turned towards a complex structure composed of several volcanic landforms of different sizes. This is due to the great variability of the tectonic and volcanic phenomena, presently showing a volcano made by two calderas, a lava dome complex and two small active cones. The largest of them is the tuff cone of La Fossa, hosted in the middle of a 3-km-wide caldera structure (La Fossa caldera), whose borders are visible on the southern and western sides of the island. Its last eruption occurred in 1888–1890. At present, Vulcano is characterized by weak shallow seismicity and intense fumarolic activity mainly concentrated within the crater of the La Fossa cone and along its rims during a recent unrest phase started in 2021, and measured with a multiparametric monitoring network.

KEYWORDS
Aeolian Islands, multihazard, plumbing system, stratigraphy, tectonics, unrest, Vulcano

1 | INTRODUCTION

The volcanic activity of the Southern Tyrrhenian Sea dates back to about 1.0–1.3 Ma, during which several (older) seamounts along with seven emerging volcanic edifices were formed (e.g., Argnani & Savelli, 1999). The latter constitute the Aeolian Islands archipelago (Figure 1). On the whole, these volcanic systems are ring-shaped, while the huge Marsili seamounts located in the middle of the homonymous basin complete the regional setting. The Moho discontinuity is at a variable depth all along the archipelago: from about 20 km in the central sector, the Moho deepens towards the west below Alicudi–Filicudi (~25 km), while becoming shallower towards the east in correspondence with Panarea–Stromboli (15–17 km) (Pepe et al., 2000; Ventura et al., 1999). A broad spectrum of geophysical studies (Chiarabba et al., 2005; Chiarabba & Palano, 2017; Faccenna et al., 2001; and references therein) indicate that the process of active subduction involving the NW-dipping and retreating Ionian slab affects the NE lithospheric region of the Aeolian arc and is limited to the SSW by the presence of the Tindari–Letojanni Fault (TLF; Figure 1). This is an NNW–SSE dextral strike-slip fault system that dominates the tectonics along the Lipari, Salina and Vulcano ridges up to NE Sicily, giving rise to a broad shear zone also punctuated by small submarine centres (Barberi et al., 1994; Bonaccorso, 2002; De Astis et al., 2003; Ventura, 1995; Ventura et al., 1999). Along with Stromboli, Vulcano is the youngest among the volcanoes of the Aeolian arc, and it is entirely made up of volcanic rocks (Peccerillo, 2005). The island was formed through a complex geological history characterized by the progressive shifting of volcanic activity from the SSE to the NNW. For this reason, Vulcano displays several edifices and morpho-tectonic lineaments, which

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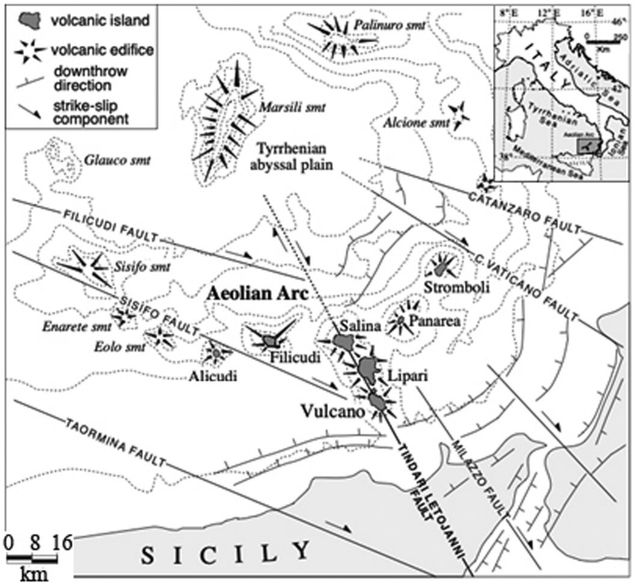

FIGURE 1 Simplified structural map of the southern Tyrrhenian region and morpho-bathymetric map of the Aeolian archipelago (modified after De Astis et al., 2003; Romagnoli et al., 2013; Ventura, 2013).

Significance statement

This review of Vulcano Island (Southern Italy) covers tectonic, volcanological and hazard features that have characterized, and still characterize, the long geological history of this active volcano. Importantly, Vulcano Island has been experiencing a phase of unrest since 2021. This work aims at synthesizing the abovementioned aspects in the broader context of geodynamic and magmatic processes that are peculiar to the island. The review ends with an open issue regarding any relationships among tectonic and eruption aspects at Vulcano, as the ones among geodynamics and geochemistry/petrology are already known. In other words, we do think that the ways in which tectonic structures can affect eruption styles/sizes through ascent rate and magma fragmentation (effusive, explosive, multistage calderas) deserve further attention at active explosive volcanoes.

reveal that the size and intensity of the eruption styles were variable and that repeated calderic collapses occurred over time. All temporal attributions in ka are referred here to BP (before present). The recent eruption activity (<15 ka) appears to have been controlled by the activity of N–S trending faults and fissures, with E–W distension and a minor or negligible contribution from strike-slip tectonics. Although the main relationships among regional tectonics and geochemical suites are known (Continisio et al., 1997; De Astis et al., 2003; Mazzuoli et al., 1995; Monaco & Tortorici, 2000), other relationships among such tectonics and eruption style and size (through ascent rate and magma fragmentation) at the scale of a single eruption are not fully known. This is particularly true at those volcanoes that have shown in their geological history very different types of eruptions, e.g., from effusive (no magma fragmentation) to multi-stage caldera (structural control) ones, and Vulcano is an example of that.

Vulcano Island covers an area of ~21–22 km^2 and reaches a maximum height of 500 m a.s.l. (Mt. Aria), which is a relief that developed after the collapse of the older stratovolcano (Primordial Vulcano). The base of this stratovolcano is at ~1000 m b.s.l. As determined by Keller (1980) and De Astis, Lucchi, et al. (2013), Vulcano consists of different volcanic landforms that formed between ~130 ka and present time, becoming gradually younger from S–SE to N–NW. Several volcano-tectonic structures (vc1, vc2, vc3, vc4, vc5, vc6; Figure 2) define Il Piano and La Fossa multistage caldera depressions, and they have left four main clearly visible landforms: the Primordial Vulcano stratocone, the Monte Lentia dome field and the Vulcanello and La Fossa cones (De Astis et al., 1997; Keller, 1980). Many other minor eruptive centres (Monte Luccia, La Sommata, Monte Rosso and Monte Saraceno) are also present, which are mostly located along the rims or intersections of – and sometimes within – the caldera morphologic depressions (De Astis, Lucchi, et al., 2013; Figure 2). The early stratocone known as Primordial Vulcano, the summit of which was truncated by the formation of Il Piano caldera, composes all the southern coastal sectors of the island, with average slope angles of 25–35°, crosscut by several metre-scale dykes. The Monte Lentia dome field is the second main volcanic landform in order of age; it partially disappeared due to the formation of the western sector of La Fossa caldera, and it consists of multiple superimposed lava domes and lava flows erupted in different phases (Figure 3b). The active 391-m-high La Fossa cone stands out in the middle of La Fossa caldera, and it represents the third dominant morpho-structural feature in the northern sector of Vulcano Island, with a 2-km-wide steep-sided tuff cone built up by the overlapping of pyroclastic successions and some lava flows emitted in various eruptive phases in the last ~5.5 ka (Figure 3a). The crater area is composed of a number of nested crater rims showing a rough NE–SW alignment. The present-day crater rim is ~500 m long, has a roughly circular shape and shows at its bottom the traces of the two anastomized vents that originated from the last 1888–1890 eruption. The peninsula of Vulcanello (with a maximum height of 123 m) is the northernmost morpho-structural feature of the island. Entirely formed in historical times (1–2 ka) along the northern border of La Fossa caldera, Vulcanello consists of three NE–SW-aligned small nested scoria cones and a lava plateau formed during the early activity of the volcanic centre. Vulcanello developed as an independent islet, and it was successively connected to the main island when an isthmus formed during the late Middle Ages concomitant with La Fossa fallout activity. The whole edifice of Vulcano is almost connected with the nearby Lipari Island complex, since just a shallow water saddle (named Bocche di Vulcano) separates the two islands north of Vulcanello (Gioncada et al., 2003). A large submerged shelf with

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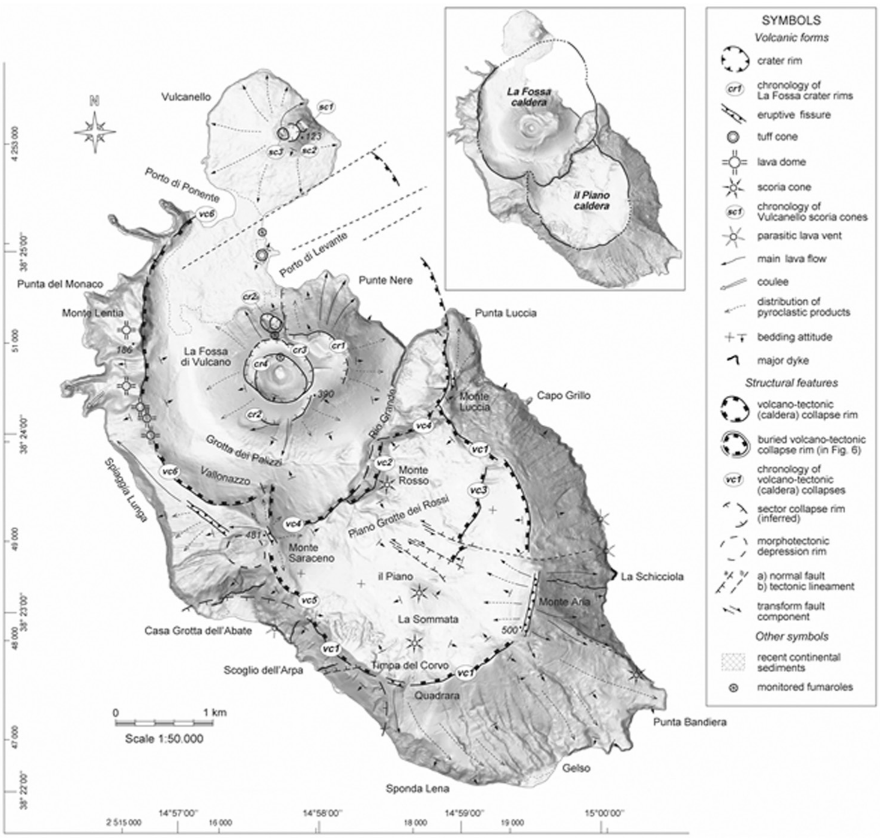

FIGURE 2 Morpho-structural sketch map of Vulcano Island, based on a DEM-shaded relief image obtained by processing data of Baldi et al. (2002), and modified after De Astis, Lucchi, et al. (2013).

an outer break at 120 m b.s.l. is present along the western coast of the island (Romagnoli et al., 2013). The volcanic landforms and their successions reflect the tectonic, geological and magmatic processes acting at the scale of the global history of the volcano. However, the interplay among processes and the ways in which they actually impact volcanic activity and hazard at the scale of a single eruption (effusive vs. explosive) are poorly known.

2 | SUBSURFACE STRUCTURE AND PLUMBING SYSTEM

Results of geophysical, exploration drilling data and structural and volcanological investigations (Calanchi et al., 1995; De Astis et al., 1997, 2003; De Astis, Lucchi, et al., 2013; Manetti et al., 1989; Ventura, 1994; Ventura et al., 1999) have shown that the uppermost part of the crust below Vulcano Island consists of 1.5–2 km of lava pile, interbedded with thick beds of unconsolidated volcanoclastic and hyaloclastic rocks, which are Holocenic in the shallower portions. This sequence basically filled the caldera depression before the occurrence of the recent La Fossa cone and Vulcanello phases of activity. The AGIP-ENEL-EMS borehole IV1 drilled in the middle of La Fossa caldera finally encountered a shallow monzodioritic intrusion at 1.35 km b.s.l. with an estimated age of 30 ka (Gioncada & Sbrana, 1991). According to geophysical and regional geology studies, the crustal layers below 2-km depth are consistent with silicic metapelites up to 5 km, granitoids or felsic granulites up to 15 km and mafic granulites of the Calabrian Arc up to the Moho (Peccerillo et al., 2006). These data also seem to exclude the current presence of large-volume magma reservoirs within the upper 0–5 km of the crust below Vulcano.

High-resolution electrical resistivity tomography (ERT), coupled with self-potential, temperature and CO_2 diffuse degassing measurements at Vulcano, has allowed proposing an interpretative structural model for the La Fossa cone interior, modelling its hydrothermal circulation (Barde-Cabusson et al., 2009; Revil et al., 2008, 2010). By means of these surveys, the main geological structures and the features of the central hydrothermal system have been identified, the latter being located within the most recent active areas on the island. The hydrothermal circulation all along the peripheral areas of the cone is influenced by its older structure, and the fluids pass through the boundaries of older crater rims and along lithological discontinuities. At about 70 m below the bottom of the youngest La Fossa crater, a resistive region has been identified by Revil et al. (2008) and interpreted as a low-porosity or dry steam-dominated body in the hydrothermal system. Instead, a conductive region has been identified below the highest-temperature fumarolic field that can be extended up to a depth of 200 m. This is probably related to the presence of alteration products and the occurrence of liquid-dominated hydrothermal circulation. A buried resistive body, also highlighted by previous aeromagnetic investigations (Blanco-Montenegro et al., 2007), has been identified in the eastern sector of La Fossa, with electrical resistivity features in the range of those expected for a lava pile or intrusive rocks. This body can be interpreted

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FIGURE 3 Significant morphological and stratigraphic features at Vulcano. (a) La Fossa cone seen from the East (Baia di Levante); (b) Lentia domes scooted from the western slope of La Fossa cone; (c) Punte Nere pyroclastic current deposits within La Roja valley; (d) Palizzi pyroclastic fallout deposits; (e) Breccia di Commenda (Caruggi) outcrop close to Palizzi area; (f) Upper Brown Tuffs ash-deposits emplaced along La Fossa caldera margin and climbing nearby Mt. Rosso scoria cone towards Il Piano. [Colour figure can be viewed at wileyonlinelibrary.com]

as a small cryptodome or a pile of tephritic lavas emplaced during an early phase of La Fossa cone activity. The hydrothermal circulation and its entity clearly depend on the subsurface structure of Vulcano in general, which in turn is the result of the cumulative (regional + local) tectonic and volcanological history of the island. However, the ways in which such a central hydrothermal system might be involved in a future volcanic activity will also depend on the magma ascent in the volcano's plumbing system. Therefore, it is clear that the volcanic activity and hazards are related to the tectonic features at various scales, but how these features can affect the single eruptive processes (effusive vs. magmatic/phreatomagmatic explosive) is not fully known.

A number of multidisciplinary studies collecting geophysical, petrological, mineral chemistry and fluid inclusions data have allowed proposing models for the plumbing system of Vulcano Island that are substantially convergent (De Astis et al., 1997; Del Moro et al., 1998; Gasperini et al., 2002). It consists of a polybaric system with several magmatic ponding zones that changed over time, and in particular, they were subjected to progressive shallowing (Zanon et al., 2003; Frezzotti et al., 2004; Figure 4a). The general volcano-tectonic regime of the island probably favoured this shallowing and consequently the complexity of evolutionary processes, especially after 30 ka. Multiple approaches for the study of the Vulcano rocks converge, indicating magma origin

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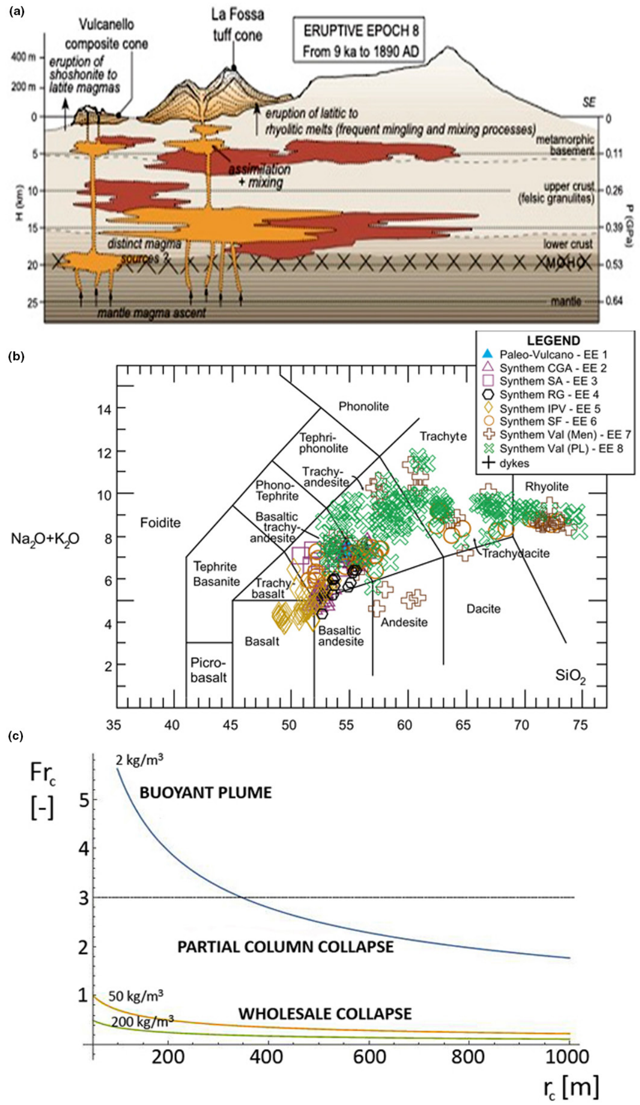

FIGURE 4 (a)) Sketch of the Vulcano plumbing system at Eruptive Epoch 8 (from De Astis, Lucchi, et al., 2013); (b) Na_2O+K_2O versus SiO_2 characterization of the Vulcano products for the Eruptive Epochs 1–8 (from De Astis, Lucchi, et al., 2013); (c) General physical conditions synthesizing some of the main eruption source parameters in explosive eruptions (jet velocity and density, crater dimension, gas content and clast componentry) through the densimetric Froude number at the crater (F_c), where r_c is the crater radius (from Doronzo et al., 2022). [Colour figure can be viewed at wileyonlinelibrary.com]

and storage horizons at ~20–21 km (Moho limit), 8–13 km and 2.8–5.5 km depths and a very shallow ponding zone at 1–2 km beneath La Fossa cone active in recent times (De Astis, Lucchi, et al., 2013 and references therein). Even the most recent petrological and gas geochemistry studies (Aiuppa et al., 2022; Costa et al., 2020) do not provide alternative models for the plumbing system of La Fossa cone, if not to reiterate this polybaric setting characterized by multiple magma reservoirs.

Considering the whole volcanic history, Vulcano has erupted magmas of variable composition, ranging from basaltic to rhyolitic, with the widest SiO_2 range for products from a single island among all the Aeolian archipelago. On the other hand, most of them fall in the compositional fields of the SHO series (shoshonite/latite/trachyte), while minor parts are high-K calc-alkaline and K-alkaline rocks, some being slightly undersaturated in silica (Francalanci et al., 1989; Peccerillo et al., 1993; De Astis et al., 1997; Calanchi et al., 2002; Peccerillo, 2005; Figure 4b). Such variability in the magmatic compositions recorded at Vulcano reflects both shallow-level evolutionary processes and the generation of geochemically distinct types of primary melts from different mantle sources. The evolutionary processes affecting the Vulcano magmas have been complex and variable both in space and time. The literature reports modelling by AFC (assimilation + fractional crystallization) or AFC coupled with refilling (De Astis et al., 2000; Del Moro et al., 1998) as processes that often occurred for the older magmas. The higher degree of evolution reached by the magmas in the last 30 ka reveals a change in the differentiation mechanisms, with a dominance of fractional crystallization with respect to previous assimilation and refilling/mixing processes (Peccerillo et al., 2006). The compositional features of the rocks younger than ~21 ka mark a further transition for the Vulcano magmas towards a more complex magma dynamics and evolution, as they result from the contributions of reservoirs at different depths (De Astis, Lucchi, et al., 2013). Most of the rocks erupted during the Holocene reveal complex mineral assemblages and zoning patterns, with frequent evidence for disequilibrium (reabsorbed phenocrysts, reaction rims and/or bimodal intra- and inter-mineral compositions), indicating clear evidence both for mixing and mingling processes occurred in the upper crust (Clocchiatti et al., 1994). Rhyolitic lava flows from La Fossa cone are obsidians carrying pink to reddish enclaves, which have a latitic to trachytic composition, a variable shape and size and often show embayments and rotational features. Even the products from the last eruption (1888–1890) contain plastically deformed magmatic enclaves (latites) at various stages of disaggregation and/or lava fragments with different compositions that changed as the eruption proceeded. Therefore, La Fossa and Vulcanello cones gave a wide variety of compositionally distinct pyroclastic products and lava flows representative of small magma volumes erupted in a restricted area (within the borders and at the centre of La Fossa caldera) and time span (Figure 4b). This implies that these multiple magma batches evolved at variable depths in independent reservoirs, but they could interact and be differently spilled before feeding the various eruptions, as documented by the mixing/mingling textures found in several rocks from the La Fossa system. Geochemical and isotopic data modelling agree in indicating the rocks genesis from complex polybaric differentiation processes (e.g., Peccerillo, 2005). The merging of petrological and very recent gas geochemistry data (Aiuppa et al., 2022) confirms the occurrence of a shallow La Fossa magma system consisting of small magma batches with different compositions that, in terms of hazard, might interact during pre-eruptive and eruptive phases. In particular, these data point to the current presence of a magma reservoir at 3.5–4 km depth, passively degassing below La Fossa

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cone and receiving fluid and melt inputs from deeper magma reservoirs (Mandarano et al., 2016; Selva et al., 2020; Figure 4a).

In the conceptual model proposed by Peccerillo et al. (2006) for the plumbing system of Vulcano Island, the magma ascent occurred in the past by buoyancy, in agreement with the density data of the crustal layers. In historical epochs, the shoshonitic basaltic melt that erupted from Vulcanello might have risen directly from the Moho to the surface, undergoing weak FC. For the La Fossa cone eruptions, this poorly evolved magma might have been stored at crustal depths (3–5 km), undergoing degassing and differentiation, to finally produce intermediate and/or evolved magma batches. This magmatic setting is in agreement with that inferred by gas and rock geochemistry (Aiuppa et al., 2022, and references therein). Also in this case, the main relationships between regional tectonics and the production of the erupted magmas are basically known (Continisio et al., 1997; De Astis et al., 2003; De Astis & Ventura, 2002; Mazzuoli et al., 1995; Monaco & Tortorici, 2000; Ventura & Vilardo, 1999; Vigneresse et al., 1999). However, the stress fields coupled with the thermo-mechanical properties of the magma and magma reservoir(s) need to be further investigated in terms of eruptible magma bodies, future eruption style/size, rate of explosivity and associated volcanic hazards and interaction with pre-existing tectonic structures (Selva et al., 2020). Different behaviours of an eruption jet can occur depending on the various eruption source parameters (jet velocity and density, crater dimension, gas content and clast componentry; Figure 4c). As an example, a relatively large structure, likely involving a large crater dimension or a fault, can affect the eruption dynamics by producing pyroclastic currents instead of a buoyant plume rising up into the atmosphere. Such interaction of variably degassed magma, perhaps with tectonic structures, may impact magma fragmentation and eruption jet dynamics (Dellino et al., 2011), which is something that deserves further investigation from a multidisciplinary perspective.

3 | ERUPTION HISTORY

Since its last eruption occurred from 1888 to 1890, Vulcano has remained dormant but with repeated phases of unrest: between 1916 and 1924, 1977 and 1980, 1987 and 1993, during 2004–2005, 2009 (?) and finally, the one still in course began between August and September 2021 (Aiuppa et al., 2022 and references therein). However, during its eruptive history, Vulcano Island experienced various long periods of quiescence that, in some cases, lasted many thousands of years, with renewal of activity after volcano-tectonic events or changes in the position of the eruptive centres. The last 1:10,000 geological map for this island is by De Astis, Dellino, et al. (2013), and it reports both the description of the recognized volcanic units according to modern stratigraphic principles – which adopt unconformity-bounded units combined with lithosomes and formations (lithostratigraphic units) – and the main steps of the volcanological history of Vulcano as the result of distinct eruptive epochs (EEs) (De Astis et al., 1997, 2006; Dellino & La Volpe, 1997; Lucchi et al., 2008, 2013; Dellino et al., 2011; Di Traglia et al., 2013; Rosi et al., 2018; map in Figure 5). This long and quite complex eruptive history can be subdivided into 8 main EEs in a time span between 127 ka and the present time. These are the major stages of the construction of Vulcano, and generally developed over hundreds or a few thousand years under direct control of the major volcano-tectonic structures. The EEs are separated by intervals of quiescence with variable time duration that are often associated with the recurrent volcano-tectonic collapses producing the multi-stage Il Piano and La Fossa calderas. Volcanism during each EE can display a wealth of erupted products from multiple eruptive centres through different eruptive styles and different chemical compositions of their products. The EEs may be further subdivided into successive sequences of eruptions (developing over years to hundreds of years) or discrete eruptions, which are separated by shorter intervals of quiescence, giving rise to minor erosional unconformities and palaeosols (Figure 5).

The oldest products exposed on the island of Vulcano crop out along the steep western coastal cliff (Capo Secco) as a rather thick pile of lava flows, characterized by an inland-dipping (eastwards) bedding attitude opposite to that of the overlying Primordial Vulcano lavas. This partly dismantled a small shield volcano dated at 127–113 ka that represents EE 1. The Primordial Vulcano stratocone (117–101 ka) was constructed by thick successions of lava flows alternating with variably welded scoriaceous fallout eruption units, corresponding to EE 2. The presence of discontinuous planar- to cross-bedded pyroclastic deposits along the outcrops of its flanks indicates that some hydromagmatic explosive eruptions, giving rise to dilute pyroclastic currents, also occurred. Some small, eccentric lava flows and scoria cones are also present on the old stratocone flanks. Afterwards, the stratocone collapsed, forming Il Piano Caldera (vc1), and the effusion of a sequence of lava flows (shoshonite basalts to leucite-bearing shoshonites) progressively infilled the W-SW sector of Il Piano caldera, corresponding to EE 3 (99.5 ka). This EE was interrupted by the volcano-tectonic collapse vc2, which is the first stage of the La Fossa caldera formation (SE border), which occurred between 99.5 and 80 ka.

The EE 4 (78 ka) took place after about a 10-ka-long period of quiescence and erosion, in particular through eruptive fissures and vents both located along the rims of the Il Piano caldera and within the caldera depression. Mt. Aria and Timpa del Corvo were the most important volcanic centres active during this EE. Their products are largely represented by lava flows further infilling the Il Piano caldera depression, but the Monte Aria fissure also gave rise to a thick pyroclastic succession composed of stratified deposits, as dilute pyroclastic currents alternated with a few strombolian fallout layers.

The EE 5 took place after a volcano-tectonic collapse (vc3) and was largely characterized by eruptive activities that filled Il Piano caldera between 70 and 42 ka from vents, which are only partially still visible (e.g., Monte Rosso, Monte Luccia) or are inferred to be present somewhere in the La Fossa caldera. Basically, these vents produced thick pyroclastic successions that are widely exposed

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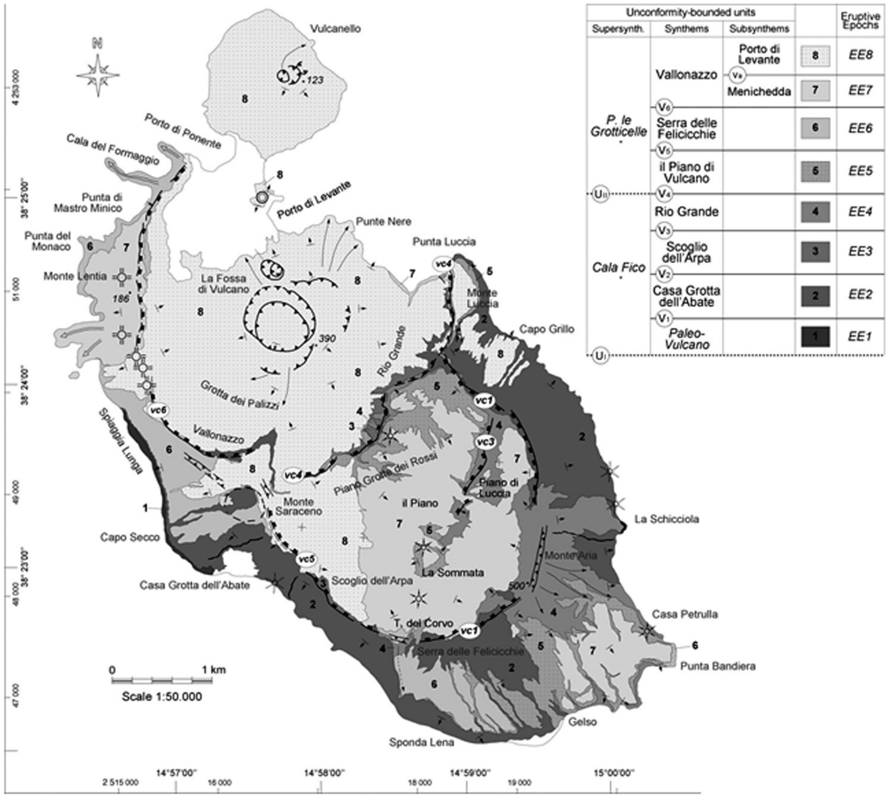

FIGURE 5 Sketch of the Vulcano geological map, with the indication of the unconformity-bounded units and the corresponding EEs (eruptive epochs; modified after De Astis, Dellino, et al., 2013).

in the flattish area of Il Piano and subordinately crop out along the southern and western flanks of Vulcano. A significant strombolian activity forming La Sommata scoria cones within il Piano and along a fissure roughly NNE–SSW-trending was responsible for the emission of the most primitive basalts recorded along the Vulcano history.

The EE 6 (28–21 ka) was associated with western eruptive fissures, giving rise to the early stages of the Monte Lentia dome field and various effusive and explosive products, among which Spiaggia Lunga, Quadrara scoriae and/or pumice blankets are the most important.

The EE 7 marks a further shifting of the eruptive centres in Vulcano history, passing from the western side towards the northern or eastern sector of the island within the multi-stage La Fossa caldera and being a prelude to the formation of La Fossa cone. They erupted both lava flows (e.g., la Roja) and pyroclastic currents. The beginning of EE 6 and EE 7 is marked by some volcano-tectonic collapses (vc4 and vc5, respectively), and by periods of quiescence and erosion followed by shifting of the eruptive centres.

Throughout the EEs 5–6-7 and just at the beginning of the EE 8, several phreatomagmatic eruptions generating medium-to-high-energy pyroclastic currents and minor fallout activity occurred. They were able to spread for many km and emplace reddish-brown to grey ash tuffs with homogeneous lithological, textural and sedimentological features. These deposits are recognized in the stratigraphic sequences of the Aeolian Islands and up to northeastern Sicily and are called Brown Tuffs (BT). Detailed studies by Lucchi et al. (2008, 2022) and Meschiari et al. (2020) confirm that The Brown Tuffs span the last 80 ka.

The EE 8 took place after a volcano-tectonic collapse (vc6) and involved explosive to effusive activities from Mt. Saraceno (8.9–8.3 ka) and some other undefined centres within La Fossa Caldera, as well as the formation of small domes and lava flows (8.5 ka) along its western border. However, it is the manifold activities from La Fossa cone and Vulcanello that constitute most of the volcanism of this EE. La Fossa cone was built during the last 5.5 ka (up to historical times) in the middle of La Fossa caldera through recurrent hydromagmatic explosive phases of activity, which gave rise to multiple dilute pyroclastic currents and minor fallout deposits. A few viscous lava flows and a couple of significant pumice fallout blankets are also present along the eruptive sequences of this volcano. Noteworthy, the volcanic history of La Fossa cone shows many eruptive periods lasting for months or years, with very long sequences of explosions associated with repetitive, weak and non-sustained eruption columns and characterized by ballistic trajectories of bombs and blocks and by the formation of pyroclastic currents. These can be considered typical vulcanian cycles, as documented by Mercalli and Silvestri (1891), who observed the 1888–90 eruptive period. The vulcanello composite cone (three small coalescent NE–SW-aligned scoria cones) stands on a lava platform that progressively emerged during historical times (2 ka) as the result of three distinct phases of strombolian to mild hydromagmatic activity, which occurred along the northern edge of the La Fossa caldera. In the period between about the 9th and 17th centuries, La Fossa cone and Vulcanello eruptions closely alternated, almost overlapping, and some pyroclastic deposits from La Fossa centre can be found at Vulcanello. The formation of the isthmus connecting the two eruptive centres also appeared around the year 1525. Both during the cycles of vulcanian activity and

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periods of volcanic quiescence, the occurrence of lahar deposits was recorded in the La Fossa stratigraphy.

All unconformities in between the various EEs are thus characterized by angular discordances due to erosion surfaces. Basically, they correspond to periods of quiescence and erosion after variably significant volcano-tectonic events took place. In particular, a shifting of the eruptive centres occurred during EE 2, EE 6 and EE 7, meaning that the previous volcano-tectonic events had a first-order influence on the eruptive activity.

3.1 | Eruption activity

The total erupted magma volumes in the whole history of Vulcano Island are difficult to calculate given its nature as an island, which has seen a large part of the pyroclastic products end up in the sea. This is especially true for those related to the Brown Tuffs eruptions, probably representing the largest erupted volumes (Lucchi et al., 2008). During historical times (last 2 ka), the volcanic activity at Vulcano was almost continuous, both from La Fossa and Vulcanello cones, in which open and closed conduit conditions alternated through the occurrence of two reservoirs. The former was a shallow network of small magma reservoirs (at ~2–4 km depth) often mutually interacting and giving rise to phreatomagmatic, mild to violent vulcanian activity and effusive episodes at La Fossa cone. The latter was a much deeper reservoir characterized by a fast rise of shoshonitic magma from the Moho and by short storage at shallow depth, generating the Vulcanello lava flows and strombolian activity.

The following types of eruption events are the most recurrent in the volcanic history of Vulcano Island (Biass et al., 2016; Bonadonna et al., 2022; De Astis et al., 1997; Dellino et al., 2011; Di Traglia et al., 2013; Rosi et al., 2018; Selva et al., 2020):

3.1.1 | Phreatic eruptions

These are events usually (often) represented by convective columns, ballistic trajectories and coarse-grained pyroclastic currents. They can cause the opening or re-opening of new vents. Lithic-rich, massive to stratified, matrix-supported pyroclastic deposits are generally emplaced during these eruptions (i.e., Caruggi Formation ca1 member, aka Breccia di Commenda), suggesting that concentrated pyroclastic currents may sometimes occur at Vulcano (Figure 3e). Lithic fragments are mainly hydrothermally altered rocks, showing a silicic and advanced argillic facies. There is more than one example of these eruptions recorded in the La Fossa formations, both as starting events of eruptions evolving into phreatomagmatic events (e.g., Pietre Cotte Fm.) and just phreatic phenomena, such as in the Caruggi Formation. Those events identified on the basis of the field deposits and attributed to the ones described in historical chronicles occurred in 1444 and 1727 (Di Traglia, 2011).

3.1.2 | Vulcanian eruptions

According to Mercalli's description (1891), these eruptions are characterized by strong explosions, ballistic trajectories of bombs and blocks, and the formation of pyroclastic currents. In more modern terms, we can define as follows: short-lived and transient (few minutes), vent clearing, cannon-like initial blasts, forming the typical mushroom-shaped eruption column just above the vent, followed by dilute pyroclastic currents and ballistic trajectories of abundant, metre-sized bombs and blocks close to and around the vent (Figures 6a–c). Consequently, the pyroclastic deposits consist both of fallout tephra layers dispersed on areas limited to the island (apart from the fraction of very fine particles) and dilute pyroclastic current deposits (Figures 3c–d). The latter are generally thin, cross-laminated ash/lapilli deposits, confined to the summit of the La Fossa cone and along its slopes, or radially widespread in the calderic area. Complex intercalations of pyroclastic current deposits in the form of thinly laminated, plane-parallel to dune-bedded ash beds and fallout deposits are visible on the La Fossa flanks.

3.1.3 | Pyroclastic fallout events

Fallout tephra deposits are poorly to moderately sorted, with lapilli/bomb layers, as particularly observed in the Grotta di Palizzi 2 Formation (Figure 3d). They are composed of an inverse-graded layer of rhyolitic pumiceous (rare obsidian) bombs and lapilli found at the base and a 2-m-thick normal-graded blanket of trachytic pumiceous lapilli and bombs with isolated bread-crust bombs towards the top. Scoria fall layers from strombolian activity are present around the Vulcanello cone.

3.1.4 | Effusive eruptions

Lava flows represent a significant part of the erupted magma in the Vulcanello activity, while they are limited for La Fossa cone to five lava flows cropping out around the cone: Punte Nere, Palizzi, Commenda, Pietre Cotte and Campo Sportivo (the latter having almost disappeared due to anthropic activity).

3.2 | The Brown Tuffs

The largest known eruptive events in all volcanism on the island of Vulcano are those related to the Brown Tuffs (BT), which are ash deposits widely distributed and represented in the stratigraphy of the seven Aeolian Islands (De Astis et al., 1997; De Astis, Lucchi, et al., 2013; Lucchi et al., 2008, 2022; Meschiari et al., 2020; Figure 3f). Such deposits have been found even at Capo Milazzo, in the northeast of Sicily. Detailed stratigraphy and tephrochronology, along with available radiometric age data, suggest that the BT were formed in a long time span from about 80 ka to 4–5 ka (EEs 5–6–7 and beginning of

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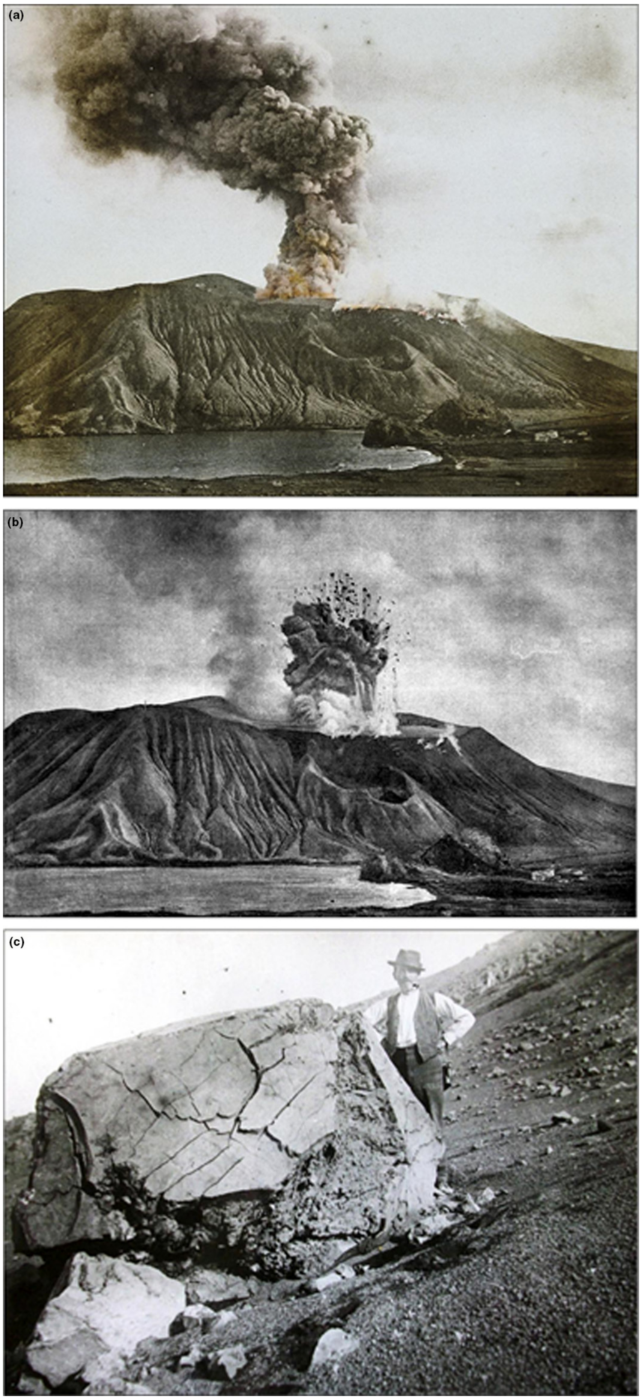

FIGURE 6 Vintage images showing eruption column (a), eruption jet and ballistic trajectories (b) and bread-crust bomb (c) of the 1888–1890 last Vulcano eruption (from Mercalli & Silvestri, 1891). [Colour figure can be viewed at wileyonlinelibrary.com]

EE 8; the latter age represents the temporal reference of the above pyroclastic products of Punte Nere at Vulcano). Interestingly, the most complete succession of the BT crops out at the island of Lipari (a few km to the north from Vulcanello) and is characterized by different units that can be subdivided into each other by the presence of widely distributed tephra layers, of local volcanic products, of palaeosoils and epiclastic deposits and locally of erosive surfaces (Lucchi et al., 2008). In particular, the presence of tephra layers related to eruptions from Ischia (56 ka) and Monte Guardia at Lipari (20–22 ka) has allowed to subdivide the BT into an upper unit (UBT, 5–20 ka), an intermedia unit (IBT, 22–56 ka) and a lower unit (LBT, 56–80 ka), which can all be correlated at the regional scale. The units of the UBT can be correlated with the pyroclastic products of Piano Grotte dei Rossi on the island of Vulcano. This correlation is based on stratigraphy, lithological and textural similarities, morphoscopy of glass fragments, composition, thickness and grain size. Such units were generated by a pulsating hydromagmatic explosive activity, which triggered pyroclastic currents through a vent located inside the La Fossa caldera. This is a genetic hypothesis constrained by the compositional features coherent with magmas that erupted at Vulcano in the same time interval. The co-ignimbrite ashes and/or the ones sedimented from sustained eruptive columns have been found on the islands of Salina, Lipari and Capo Milazzo, testifying that these BT products were widely distributed (Lucchi et al., 2022). Similarly, the LBT and IBT were generated by recurrent hydromagmatic explosive activity of the same type as the UBT, and this has been addressed by lithological and textural uniformities. Moreover, it has been found a correlation, based on stratigraphy, lithology and composition, between the units of the IBT and the pyroclastic products of Monte Molineddo 3 at Vulcano, testifying the origin of the IBT through a vent related to the feeding system of the La Fossa caldera.

4 | NON-ERUPTIVE PERIODS

Non-eruptive periods at Vulcano have represented a time span roughly ranging from tens to hundreds of years. This is documented for the whole Vulcano history through chrono-stratigraphical evidence, and in particular for the Holocene period. Landslides and volcanoclastic flows, including the whole spectra of secondary gravity-driven mixtures of volcanic material and water, were emplaced during La Fossa's volcanic history, travelling and accumulating mainly on the slopes and at the foot of the cone. The already mentioned unrest episodes, which occurred in the late 1970s, were tracked by a comprehensive geochemical and geophysical surveillance network, now run by the INGV (Istituto Nazionale di Geofisica e Vulcanologia), implemented on the island since 1981. Currently, La Fossa cone is characterized by low-level seismicity and intense hydrothermal activity, small ground deformations and rapid changes in the geomorphology due to the now frequent heavy rains, which are deepening the cuttings on flanks and also eroding the mainly loose deposits that cover the rims and slopes of the edifice (Aiuppa et al., 2022; Bonadonna et al., 2022; Diliberto et al., 2021; Selva et al., 2020). Going into details related to the last decades:

4.1 | Seismic activity

Seismic activity is strictly dependent on the dynamics of the strike-slip Tindari–Letojanni regional fault system (Bonaccorso, 2002;

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Bonforte & Guglielmino, 2008). Considering the so-close Lipari and Vulcano volcanic systems, the spatial distribution of the hypocentres shows Vulcano Island with the highest number of events, while Lipari is characterized by a lower seismic rate. Most of the earthquakes occurred within the first 15km of the crust, and the shallower ones are below Vulcano Island. In the last 40years, the seismic strain release of the Aeolian region has been roughly constant, interrupted by a few abrupt releases due to strong earthquakes: April 1978 (M=5.5), May 1980 (M=5.7), August 2010 (M=4.6) (Alparone et al., 2019 and references therein) and December 2022 (M=4.5) (http://terremoti.ingv.it/). The HF volcanic seismicity characterizing the early 1–1.5km below La Fossa cone showed a main strain release during the period 1986–1994, and in particular in 1988 and 1992 (Montalto, 1994). However, a seismicity consisting of the so-called VLP (very long period) events, which are attributed to fluid pressurization and resonance of fluid-filled cracks, is normally present. Periodic phases of increased output flux and temperatures of the emitted fluids from the fumaroles area of La Fossa cone are generally accompanied by an increase in volcanic seismicity occurrence. The current unrest phase is also characterized by the presence of VLP events with a frequency content lower than that observed for the micro-earthquakes typically recorded at La Fossa cone. These seismic signals have never been recorded in the last 15years (a “broadband” network capable of identifying them was then installed), and their presence is compatible with the observed increase in fluid output that induces pressurization of the ducts and consequently resonance phenomena. These observations are consistent with what emerges from the geochemistry data (Aiuppa et al., 2022; Cannata et al., 2012; Italiano et al., 1998 and references therein). As for the fracturing seismicity (earthquakes) linked to the dynamics of the tectonic structures present in the Vulcano area, it has not shown any significant variations, remaining at a very low level.

4.2 | Hydrothermal activity

The degassing area of Vulcano is concentrated in the northern part of the island: La Fossa cone, Il Faraglione, Baia di Levante, Palizzi and some locations in the Vulcano Porto village (e.g., Camping Sicilia) (Capasso & Inguaggiato, 1998; Chiodini et al., 1993; Madonia et al., 2015; Paonita et al., 2002; Selva et al., 2020). The fumaroles located along the northern crater rim and in the inner walls of La Fossa crater are the most active. After the 1888–1890 last eruption, for over twenty years, the gas emissions have suffered a setback and sharp decline. Then, the gas outputs have gone through different stages of temperature and compositional variability identified as unrest episodes (or periods): 1916–1924, the crater fumaroles increased to T_{max}=615°C; 1977–1980, a new warming phase with multiple fluctuations associated with significant variations in the contribution of magmatic gas species (CO_2, SO_2 and H_2S); 1987–1993, a repeated increase of the fumarole temperature at the crater rim (up to 650°C in 1991 and 690°C in June 1993) and a simultaneous growth of the exhalation surface and emission rate. The temperature and gas outputs gradually lowered in the following years, but other periods of higher intensity and areal expansion occurred in 2004–2005 and 2009. Starting in August/September 2021, the INGV monitoring systems have recorded variations of some geophysical and geochemical signals, especially those linked to the activity of the hydrothermal system (Figure 7). A sharp variation of the temperature and gas composition was measured at the crater fumaroles, with a large increase especially for CO_2, SO_2 and He ratios (Aiuppa et al., 2022). The temperature reached maximum values of 380–400°C. In October and November 2021, the degassing expanded, affecting also the areas along the southern and eastern edges of the cone and at its foot, within the La Fossa caldera. In some areas, soil CO_2 degassing and the thermal aquifer recorded strong anomalies (e.g., Camping Sicilia well and Baia di Levante area). In early to mid-November 2021, the unrest reached its climax.

4.3 | Ground deformation

Deformation at Vulcano has been monitored by GPS, EDM, GNSS and levelling surveys since 1975. Since the 1990s, a permanent sensor network, which presently counts with 5 clinometers and 5 GNSS stations, has been installed. Geological data, measurements carried out through these monitoring activities, and other research activities indicate that in the last decades, La Fossa cone was characterized by a general low subsidence (or weak deflation) and just a couple of periods of inflation during 1975–1980 and 1984–1989 (Alparone et al., 2019; Gambino & Guglielmino, 2008). As shown by gas output, ground deformation has displayed a change in 2021: starting from mid-August, the GNSS measurements have shown a certain expansion of the La Fossa cone area. This process accelerated in mid-September and reached a peak in mid-November, with a maximum uplift of 3cm on the northern sector of the cone. This variation has also been recorded by the InSAR measurements (CNR-IREA and INGV), with an associated horizontal symmetric expansion on both the eastern and western La Fossa flanks. Basically, such occurrences of ground deformation at Vulcano Island appear to be linked to the geothermal system rather than to magmatic and/or tectonic sources, and this introduces greater complexity in the monitoring activities of the volcano, suggesting the importance of integrating and improving geophysical and geochemical data in order to distinguish “hydrothermal” ground deformation episodes from (eventually) magmatic ones (Aiuppa et al., 2022).

4.4 | Gravimetry time series

Measurements and collections of microgravimetry data at Vulcano, performed since 1981 through periodic field surveys, have shown short-term gravity changes over a time span of a few months, generally not larger than 20–40 GaL. These variations were detected in the central-southern part of the island, at the base of the La Fossa cone. The mechanisms responsible for them are the fluid migration

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FIGURE 7 Panoramic photo of La Fossa crater with monitoring instruments installed and the clear fumarolic activity during the last unrest (since 2021), and in the background Lipari Island and then Salina Island. [Colour figure can be viewed at wileyonlinelibrary.com

through shallow levels of the crust (500–1000 m) and the cyclic water-to-vapour transformations (Di Maio & Berrino, 2016 and references therein).

4.5 | Present situation

After the peaks reached in November 2021, the monitored parameters started to display slow and discontinuous decreasing trends, although some of them remained significantly above the background for several months and still are (see Federico et al., 2023 for a detailed overview of all geophysical and geochemical parameters).

5 | MULTIPARAMETRIC MONITORING NETWORK

A modern and integrated instrumental monitoring network has been active at Vulcano since 1981, playing a fundamental role in increasing knowledge about the volcano dynamics. This network was improved after 2002 as a consequence of the regional increase in that year of the volcanic activity affecting the Southern Thyrrenian Sea and NE Sicily (i.e., the Etna eruption in October, submarine paroxysmal degassing close to Panarea Island offshore in November and the Stromboli eruption in December). The last unrest phase has led to careful strengthening of the INGV monitoring system since autumn 2021.

La Fossa cone entered a new phase of unrest between August and September 2021. The monitoring system recorded a sudden variation in seismicity, ground deformation, fumarole temperatures, soil and plume degassing. These variations were interpreted as due to the fast vaporization and expansion of the hydrothermal system (Federico et al., 2023), set at depth >1.5 km b.s.l. as a hypothesis. At the same time, fumarole chemistry showed clear-cut variations related to the dominant contribution of the magmatic gas over the hydrothermal one. The CO_2 content and the He isotope composition of the magmatic source revealed the appearance of a more primitive magma, compared to that feeding the fumaroles in the previous period, during the climax of the unrest. The signs of the enhanced contribution of magmatic gases in the fumarole gases were already evident since 2018. Therefore, the 2021 unrest appears to have been the outcome of a long-lasting preparatory phase. The systematics of gas species together with C and He isotopes emitted from fumaroles after the first months of the unrest revealed the appearance of a different magmatic component, poorer in N_2 and ^{3}He and richer in He, S and ^{13}C. The magmatic contribution is persistently overwhelming the hydrothermal one at the time of this communication.

Nowadays, the real-time multiparametric monitoring network includes thermal and visible cameras, both permanent and temporary seismic and GNSS stations, bore-hole tiltmeters and SAR interferometry and automatic single gas and multigas-type stations (Aiuppa et al., 2022; Diliberto et al., 2021; Selva et al., 2020). An INGV info-point (Centro Carapezza at Ponente Bay) for tourists and volcano-fans is also present on the island and opened during the summertime for dissemination activities. The currently active monitoring system is managed by the INGV-OE (INGV-Osservatorio Etneo) and, for fluids, by the INGV-PA (Palermo Section) under the coordination of the INGV-CME (Centro per il Monitotaggio delle Isole Eolie), acquiring the following instrumental signals:

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- Seismicity acquired through the INGV seismic network located in the Lipari-Vulcano area, which is composed of six permanent stations (five on Vulcano), equipped with broadband three-component Trillium (Nanometrics) velocimetric seismometers and one accelerometric sensor. In September 2021, the seismic network was boosted with the installation of nine temporary stations, seven of which are located on Vulcano Island. This system provides a spatio-temporal distribution of microearthquakes and tremors, energy, source mechanisms and spectral characteristics. Seismic data are analysed daily by an INGV-OE scientific team and stored in the Aeolian instrumental catalogue;
- Ground deformation (providing vertical and horizontal displacements through 5 GNSS stations, 5 tiltmeters and InSAR);
- Geochemical and temperature variations of fumarolic fields and thermal springs (CO_2 fluxes from 13 stations; fumarolic temperatures and temperature gradients in soils; and chemical–physical parameters of fluids and water), while the single gas and multigas instruments provide continuous measurements of the CO_2, SO_2 and H_2S levels, as well as environmental parameters such as pressure, temperature and air humidity;
- Other useful information comes from 3 continuous high-precision gravimeters recently installed, as well as from real-time video shooting and volcanological field observations (opening of new fractures, changes in the level of wells, new or reactivation of fumaroles, etc.). A high-definition camera framing the northern sector of Vulcano installed at the Geophysical Observatory on Lipari Island (in front of Vulcano) and a new thermal camera positioned on the La Fossa crater rim have recently been activated. Instrumental data are combined with direct observations of La Fossa activity via satellite images and frequent field inspections. Finally, a GBRAR (Ground Based Real Aperture Radar) installed at the Geophysical Observatory is able to measure at high frequency the ground deformation on the northern slope of La Fossa cone.

It is necessary to clarify that, at the current state of knowledge, it is not possible to establish the exact timing of reactivation dynamics, which, by comparison, has never been measured before. In fact, the ascent of magma might be associated with an earthquake of large magnitude or with numerous local earthquakes of minor magnitude. Likewise, for ground deformations, rapid as well as slow dynamics might be observed.

6 | VOLCANIC HAZARD

All studies on the volcanism of the island of Vulcano (geological, geophysical and geochemical studies) have shown that the volcanic activity through time is represented by a series of low-energy eruptive events, both explosive and effusive, and occasionally by high-energy caldera-forming explosive eruptions (Dellino et al., 2011; Rosi et al., 2018; Bonadonna et al., 2022; Table 1). The relatively high frequency of the eruptions occurred through vents that gave significant effects inside Il Piano caldera, including La Fossa cone and Vulcanello. Volcanic hazards at Vulcano are caused by hydrothermal events, emission of toxic gases, landslide and volcanic s.s. (pyroclastic currents, ballistic trajectories and ash fallout) events (Biass et al., 2016; De Astis et al., 1997; De Astis, Lucchi, et al., 2013; Dellino et al., 2011; Dellino & La Volpe, 2000; Doronzo et al., 2017; Lucchi et al., 2008, 2022; Rosi et al., 2018; Selva et al., 2020). One of the most insidious risks is represented by the emission of toxic gases (CO, CO_2, H_2S and SO_2) that rise up through soil fractures (Aiuppa et al., 2022; Bonadonna et al., 2022). CO_2 is denser than air and, without any winds, is subjected to accumulation at soil level in high concentrations. It is odourless and, at low concentrations, may cause a series of minor health problems, while at high concentrations, even asphyxia. Besides CO_2, another highly toxic gas is H_2S which, on the other hand, has a strong and recognizable smell that can be detected by people even at low concentrations. This gas may affect the human respiratory system. Another type of risk, indirectly related to volcanic activity, is represented by landslide events. The cone of La Fossa has, even in ordinary conditions, an instable nature due to the high slope angle of its flanks and to fumarolic activity, which tend to reduce the cohesion and stability of rocks. In particular, on the flank of Forgia Vecchia and in those in the southern part of the island, some landslides occurred in the past (Di Traglia, 2011; Selva et al., 2020). Besides these risks, another risk can be related to the formation of tsunami waves following the entrance of major landslides into the sea, similar to what has recently occurred at Stromboli Island (Esposti Ongaro et al., 2021). Another type of risk, this time directly related to the volcanic activity during high-energy explosive eruptions, is represented by the formation and propagation of pyroclastic currents. Such currents are highly mobile and expanded and can have velocities of tens of m/s and thicknesses of several metres. They can strongly interact with the topography of the island, fill the morphological lows and climb up the relative highs (e.g., Il Piano caldera, with pyroclast volumetric concentrations up to 0.2%), loading the landscape with dynamic pressures locally up to ~5 kPa and re-distributing the erupted material on most of the island (Dellino et al., 2011; Dellino & La Volpe, 2000; Doronzo et al., 2017; Doronzo & Dellino, 2014). These volcanic events can be accompanied by ballistic trajectories of dense blocks and ash fallout (Rosi et al., 2018).

All of this volcanic hazard at Vulcano has favoured the implementation of continuous measurements of geophysical and geochemical parameters (seismicity, ground deformation, gas output) by multiple techniques (Figure 7). Moreover, field campaigns are periodically done for the measurements of some geophysical and geochemical parameters that cannot be measured by instruments in H-24 acquisition. Both time-dependent and field campaign data are automatically analysed, controlled and interpreted by researchers from multidisciplinary fields. In the last decades, La Fossa cone went through various periods of unrest documented by significant variations of the monitored parameters, which for the most recent unrest have led to the passage to the yellow alert level. Such a level represents a state of potential disequilibrium of the volcano on a scale of 4 colours defined by the Italian Civil Protection Department, where green indicates a state of

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TABLE 1 Summary table for Vulcano Island reporting the main geographical, morphological, volcanological, geochemical and hazard features (see the main text for any details related to each point).

Lat, lon	38°23′ N, 14°57′ E
Elevation	500 m a.s.l. (Mt. Aria)
Type	Stratovolcano with summit caldera
Summit ice cover	–
Dominant type of activity	Phreatomagmatic (in recent times)
Magma type	Shoshonites to rhyolites and minor basalts (HKCA to SHO suites)
Known precursors	Gas emissions, anomalous seismicity, ground deformation
Expected precursors	Anomalies with respect to the geophysical and geochemical background parameters
Eruption characteristics	Vulcanian explosions, ballistic trajectories, lava extrusions
Type of products	Pyroclastic fallout and pyroclastic currents, lava flows, debris flows
Volcanic Explosivity Index	Max VEI 1–2; most frequent VEI 1
Column height	A few km to ~12 km
Duration of eruptions	Days to years
Bulk volume tephra	Max $1.5 \cdot 10^7 m^3$
Fallout beyond 1000-km distance	–
Tephra < 63 µm at 30-km distance	–
Bulk volume lava	na
Longest lava flow	2–2.5 km
Gas emission sulfur	High
Interval between eruptions	Vulcanian (~100 years); last 400 years (open to closed conduit, tens of years)
Last significant eruption	1888–1890 (extrapolated VEI 1–2; total erupted DRE magma unknown)
Seismic episodes	~1000/year (last 5 years), M_{max} 2.8
Deformation characteristics	Deflation at La Fossa cone (from the last eruption to pre-2021 unrest)
Monitoring level	High
Current activity	Unrest
Distance to international airports	Catania 103 km, Palermo 164 km
Principal hazards	Tephra and ballistic fallout, fumaroles, pyroclastic currents, lahars, landslides

equilibrium (the less hazardous); yellow indicates a state of potential disequilibrium; orange indicates a state of disequilibrium; and red indicates a state of strong disequilibrium (the most hazardous). The readers are referred to the papers of Selva et al. (2020), Bonadonna et al. (2022) and references therein for details on the hazard and environmental impact at Vulcano Island.

6.1 | Possible scenarios based on past eruption activity

In order to identify the eruptive behaviour of Vulcano over time, an important factor is represented by the recurrence of a given category of eruptive events that have been recognized in the volcanological and stratigraphic history of the island (Dellino et al., 2011; Rosi et al., 2018; Selva et al., 2020). Such an analysis can be done at different scales: (i) at the scale of single events showing the recurrence during eruption; (ii) at the scale of eruptions showing the recurrence of events among successive eruptions (a few to hundred years); (iii) at the scale of volcanic successions showing the recurrence of events among the various successions (a few hundred to thousand years). At the shorter temporal scale (intra-eruption), the recurrence of events that gave laminated layers and exerted flow dynamic pressure from pyroclastic currents is very high. Moreover, it is to be noted that the action of events that gave ballistic trajectories of dense blocks, instead the recurrence of other events, such as lava flows/domes and scoria cones formation, is lower. At the intermediate temporal scale (inter-eruptions), the recurrence of events from pyroclastic currents is high, instead is low, but still significant, that from ballistic trajectories, and even lower from other categories of events (e.g., lava flows). At the longer temporal scale (inter-successions), the recurrence of events from pyroclastic currents is high. Considering that the last eruption of Vulcano occurred in 1888–1890, it is possible that the next eruption could belong to the succession of the present crater of the La Fossa cone. This means that the main expected phenomena could be considered as pyroclastic currents and ballistic trajectories of dense blocks. Indeed, in the stratigraphy of Vulcano Island, it is reported that there is a significant presence of pyroclastic current deposits and the occurrence of ballistic trajectories, particularly for those eruptions (e.g., Punte Nere, Caruggi) in which the hydrothermal activity system was well developed. Also, in the stratigraphy of Vulcanello, it is reported that there were lava flows and strombolian products that interfered with the northern edge of the La Fossa caldera, particularly in the last ka. However, it is to be noted from the hazard viewpoint that the stratigraphy of a volcano cannot record all past activity, meaning that the integration of geophysical, geochemical, volcanological and geomorphological data with numerical/probabilistic modelling and multiparametric monitoring (e.g., Aiuppa et al., 2022; Biass et al., 2016; De Astis, Lucchi, et al., 2013; Doronzo et al., 2017; Rosi et al., 2018; Selva et al., 2020) is necessary in the short- to long term to account for all possible phenomena, including flank instability and phreatic explosions. Also, eventual direct relationships between the regional/local tectonic structures, the magma production vs. degassing and ultimately the eruption style/size and the magma fragmentation efficiency at eruption scale are only sectorally known (De Astis et al., 2003; Dellino et al., 1990), and they probably deserve further attention in terms of the volcanic hazard at Vulcano Island.

7 | CONCLUSIONS

In this paper, the geological, petrological and structural histories, as well as the hazards and monitoring system of Vulcano Island, have been reviewed and presented. Such a compilation of all (broadly speaking) geological features can be used as a guide that bridges the complex past of this active volcano to its current activity state. On the other hand, this work has no pretension to predict the next eruption style and size at Vulcano, as it has been presented as a global summary of the Vulcano geological history. It is to be noted that the multiparametric monitoring activities are fundamental at Vulcano because they can actually measure the parameters that are useful for the short-term surveillance goals and modelling implementations. The importance of taking into account the geological past and the tectonic and petrological features of the island is related to the repetitivity of events that occurred through time, and several of their traces are present in the geological record. In other words, a synthetic but comprehensive knowledge of the history of Vulcano can be of support to the interpretation of the monitoring and modelling data, as, in general, volcanoes tend to repeat some of their activities over the long term. The regional tectonics around Vulcano may affect the magma dynamics in the long term, and this deserves further investigation, particularly with reference to how tectonic events may directly or indirectly affect eruption styles and sizes through magma fragmentation efficiency up to the scale of a single eruption. However, it is also important to note that there are other natural phenomena that tend not to be recorded in the volcanic successions. A full list of volcano multihazards can thus be compiled at Vulcano Island: gas dispersion, phreatic explosions, earthquakes, ash fallout, ballistic trajectories, pyroclastic currents, ground deformation, lahars, landslides and tsunamis. This review on Vulcano Island ends with an open question: how may a well-defined tectonic context (magma rise) and the Vulcano plumbing system (magma production/storage) affect the eruption mechanisms (magma exit) at eruption scale? Such a comprehensive question arises from the awareness that a number of general relationships between the geochemical suites of magmas and tectonic contexts are already known, but the ones between the latter and single eruptive events (effusive, explosive, multi-stage calderas) are basically unknown. In these last relationships, which are still to be explored, there might be some keys for eruption forecasting in the long term.

ACKNOWLEDGEMENTS

We would like to thank two anonymous reviewers and the editor, C. Doglioni, for their help in improving the clarity of this multidisciplinary work on Vulcano Island. The work has been partly funded by the EUROVOLC project – WP11 supporting the European Catalogue of Volcanoes, and by the INGV Pianeta Dinamico project.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: De Astis, G., Doronzo, D. M., & Di Vito, M. A. (2023). A review of the tectonic, volcanological and hazard history of Vulcano (Aeolian Islands, Italy). *Terra Nova*, *35*, 471–487. https://doi.org/10.1111/ter.12678

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