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Volcanic Stratigraphy of Lipari obsidian and sources of Neolithic artefacts

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Abstract

Obsidian is a raw material widely used in prehistoric times (“the Neolithic black gold”), and its origin is of particular interest to archaeologists for reconstructing trading patterns. Obsidian from Lipari dominates the Early to Late Neolithic archaeological assemblages in the central Mediterranean (along with that from Monte Arci, Sardinia). Here we provide a review of the volcanic and stratigraphic features of the eruptions that produced rhyolithic obsidian-bearing pyroclastic successions and lavas during the last ~50 ka in the southern and north-eastern sectors of Lipari, thus providing insights on the definition of obsidian subsources. The main eruptions are those of Monte Guardia (27-24 ka) and Vallone del Gabellotto (8.7-8.4 ka), whereas the Monte Pilato, Forgia Vecchia, Lami and Rocche Rosse eruptions lately occurred in the Middle Ages (776-1316 CE). Based on the abundance of obsidian and the distribution of outcrops, the principal obsidian subsource can be identified as the Vallone del Gabellotto pumice succession, located in the northeastern sector of Lipari. A secondary contribution may be attributed to the undated Vallone Canneto dentro pyroclastics in the central-eastern sector. Additionally, the Pomiciazzo lava coulee – associated with the Vallone del Gabellotto unit – may have provided a further, albeit limited, source; however, its significance is constrained by the limited availability of workable fragments. Potentially, also the Monte Guardia pyroclastic succession (27-24 ka) could represent an obsidian subsource, but likely due to its frequent brecciation and poor aptitude for chipping and for producing stone tools artifacts have never been found at Neolithic sites in the Mediterranean area.

Keywords: Lipari; Volcanic stratigraphy; Rhyolite; Pumice deposit; Obsidian

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1. Introduction

Obsidian is a natural volcanic glass, usually dark but transparent in thin pieces, that is highly attractive and relatively easy to work, due to frequent and very predictable conchoidal fractures (Donato et al., 2018). Obsidian is typically vesicle-poor and crystal-free and is a volcanic product of both explosive and effusive eruptions of viscous, silicic (mainly rhyolitic) magmas, often associated with highly vesicular pumices in explosive eruption deposits.

Obsidian was widely used as a raw material during the Neolithic (6000-2000 BC), the reason why it is known as the “Neolithic Black Gold”, and its origin is of particular interest to archaeologists for reconstructing trade patterns. For this purpose, archaeologists need detailed volcanological, stratigraphic and age information on the sites where obsidian was exploited, thus facilitating the attribution of artifacts and archaeological findings and the characterization and differentiation between different sites. An obsidian source may consist of one or more obsidian-producing eruptions within a restricted area (Pollard and Heron, 2008), whilst an obsidian subsource is related to an individual eruption from the same area (Freund, 2018). The distinct sources and subsources are distinguished from each other based on the age of the corresponding eruption and/or their different lithostratigraphic and geochemical characteristics (Freund, 2018).

The island of Lipari (Aeolian archipelago, southern Sicily) is a main source of obsidian in Italy, together with the other sources of Palmarola (Pontine Islands), Monte Arci (Sardinia) and Pantelleria (Freund, 2018 and references therein). Lipari's raw materials have the widest distribution in the central Mediterranean basin as indicated by the findings of its obsidian in numerous archaeological sites in peninsular Italy and Sicily, as well as in southern France and the Istrian peninsula of Croatia, and in Malta (Bigazzi et al., 2005; Tykot et al., 2013, 2019; Freund, 2018).

This paper reviews the stratigraphy of obsidian-bearing volcanic products related to eruptive activity on Lipari during the last 50 ka. It defines the main subsources of obsidian on Lipari and provides an up-to-date interpretation of obsidians in pyroclastic successions and lava domes/coulees. Among these, the Vallone del Gabellotto (8.7-8.4 cal ka) and Vallone Canneto dentro (undated) pumice successions, both referring to eruptive vents in the north-eastern sector of the island, have been generally identified as major sites of archaeological obsidian (Bigazzi et al., 2005; Tykot et al., 2006; Freund et al., 2017; Freund, 2018; Tykot, 2019). In the past, Pichler (1980) suggested the Rocche Rosse lava as an obsidian source, before the very young age of the Rocche Rosse (*1243-1304 CE*; Pistolesi et al., 2021) was established. Particularly, Bernabò-Brea (1978) was one of the researchers to suggest that most of the obsidian fragments exploited during the Neolithic on Lipari were found as clasts within the pumice deposits of these two units, and not from the volcanologically associated Vallone Canneto dentro lava dome and Pomiciazzo lava coulee. The two subsources have been geochemically distinguished by some authors on the basis of their Fe/Sr and Rb/Sr ratios (Tykot et al., 2006; Tykot et al., 2013; Freund et al., 2015, 2017; Tykot, 2017, 2019), although Donato et al. (2018) did not confirm this observation. We thus pay special attention to the volcanological, stratigraphic and age features of the Vallone Canneto dentro and Vallone del Gabellotto volcanic units. Combined with geochemical information from the literature (Donato et al., 2018), this will provide the greatest possible quantity of elements useful for the subdivision of the two subsources, together with a compilation of their main outcrops, as a basis for further archeological studies.

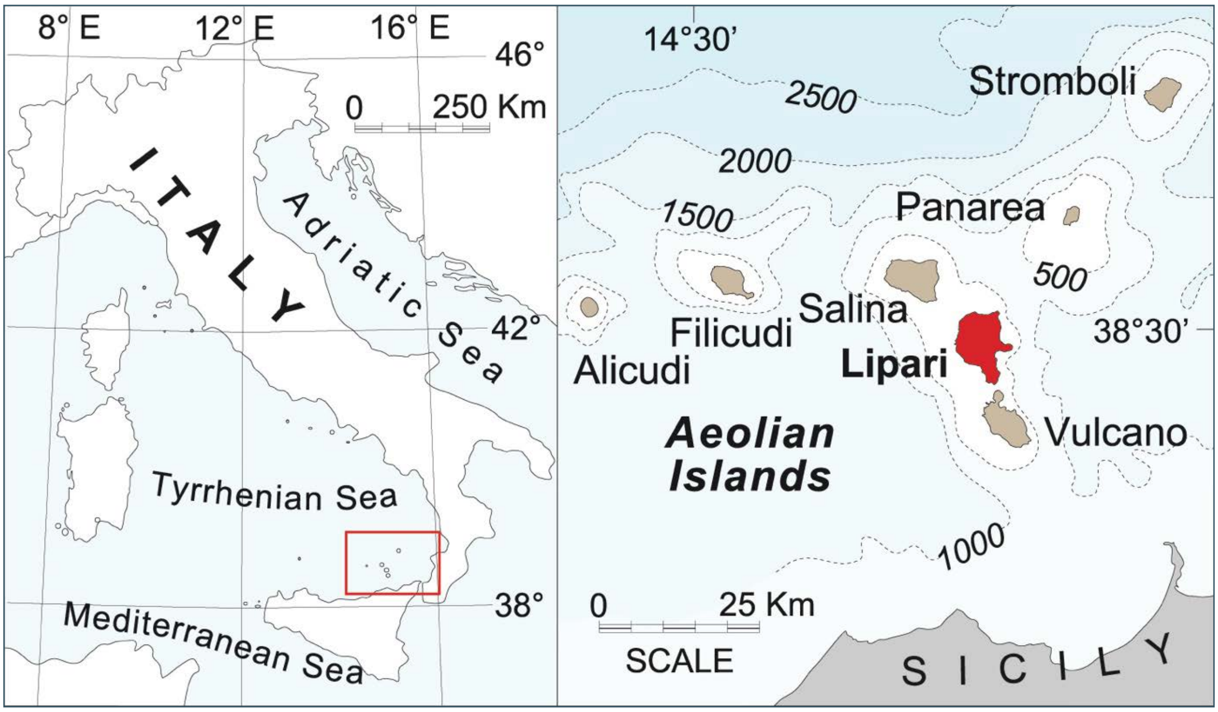

Figure 1. Localization of Lipari in the Aeolian archipelago, southern Tyrrhenian Sea (bathymetry modified from Beccaluva et al., 1985).

2. Volcanic stratigraphy of Lipari

The island of Lipari (total area of 38 km^2) is the largest in the Aeolian archipelago, an active Quaternary volcanic structure in the southern Tyrrhenian Sea (Fig. 1) resulting from subduction and post-subduction back-arc extension under the influence of regional tectonic systems (Barberi et al., 1973; Ellam et al., 1989; De Astis et al., 2003; Chiarabba et al., 2008; Mandarano et al., 2016). Lipari is the emerged culmination of a broad volcanic complex belonging to the Vulcano-Lipari-Salina volcanic belt developed along the major NNW-SSE strike-slip Tindari-Letojanni fault system (Mazzuoli et al., 1995; Lanzafame and Bousquet, 1997; D'Agostino and Selvaggi, 2004; Billi et al., 2006; Ventura, 2013; Ruch et al., 2016).

Lipari is an active volcanic system presently developing in a quiescent stage with a few low-temperature fumaroles and hot springs mostly located in the western sectors of the island. Its volcanic activity has developed between c. 267 ka and the medieval ages (Bigazzi and Bonadonna, 1973; Pichler, 1980; Cortese et al., 1986; Gillot, 1987; Crisci et al., 1991; De Rosa et al., 2003b; Tanguy et al., 2003; Leocat, 2011; Forni et al., 2013) giving rise to a large variety of lava flows, lava domes and pyroclastic deposits ranging in composition from calcalkaline (CA) to high-K

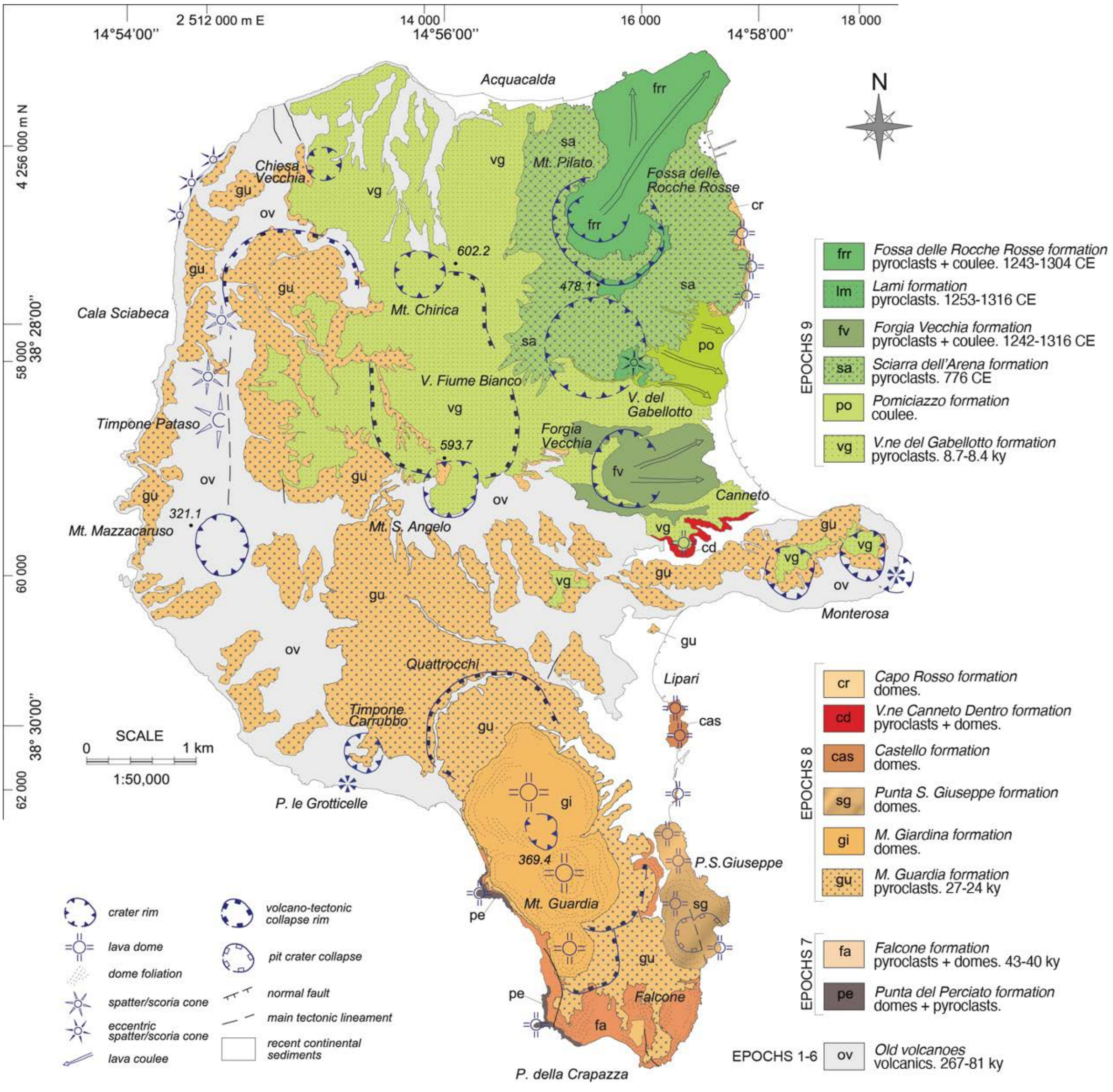

Figure 2. Geological sketch map of Lipari Island (modified after Forni et al., 2013) showing the main stages of its eruptive history (EE eruptive epochs and formations), with particular attention to the rhyolitic products erupted during the last 50 ka. Ages of Lipari volcanics are also reported in the legend.

CA basaltic andesites to rhyolites, with a notable gap of dacitic compositions (Pichler, 1980; Crisci et al., 1991; Gioncada et al., 2003; Di Martino et al., 2010, 2011; Forni et al., 2013, 2015).

According to the most recent geological mapping (Lucchi et al., 2010; Forni et al., 2013; Lucchi et al., 2013b), the volcanic stratigraphy of Lipari is subdivided into nine eruptive epochs (hereafter EE; Fig. 2) developing over tens of thousands of years and further subdivided into distinct eruptions or sequences of eruptions, each one characterized by distinctive active eruptive vents and separated by quiescence periods of varying duration, volcanic collapses and shifts of eruptive vents controlled by regional tectonics.

The early eruptions (EE1-3) developed between c. 267 and 150 ka from a series of monogenic and polygenic eruptive centres located in the western and central-northern sectors of the island, mostly producing basaltic andesitic to andesitic strombolian scoriae and lava flows. The intermediate eruptions (EE4-6) occurred between c. 119 and 81 ka from the Monte S. Angelo and Monte Chirica stratocones, in the central-northern sector of the island, and the twin Monterosa scoria cones, in the eastern sector. They produced alternating lava flows and hydromagmatic to strombolian pyroclastic products ranging in composition from basaltic andesites to andesites (and subordinate dacites). Along the western coast of the island (and subordinately at Monterosa), these products are repeatedly interlayered with marine terraces at varying elevations formed during successive episodes of sea level ingression during the Last Interglacial (between 124 and 81 ka) (Calanchi et al., 2002; Lucchi, 2019). Rhyolitic magmas, which are the object of the present paper, were erupted on Lipari during the last c. 50 ka from vents located in the southern and north-eastern sectors of the island (EE7-9; Fig. 2). The eruptions of rhyolites were typically cyclic with an early explosive phase and the final effusion of endogenous lava domes and obsidian lava coulees (De Rosa et al., 2003a; Gioncada et al., 2003; Forni et al., 2013). They occurred from vents initially located in the southern sector of Lipari (EE7, EE8a) under control of the main NNW-SSE tectonic trend and then shifted to the central-eastern (EE8b) and north-eastern sectors (EE 9) of the island along N-S and NE-SW tectonic trends.

3. Lithostratigraphy and ages of rhyolitic volcanic units bearing obsidian

Rhyolitic (obsidian-bearing) volcanic units crop out in different sectors of Lipari, interlayered with widespread tephra deposits from major explosive eruptions of Vulcano and Salina and distal fallout layers from Campania (Keller, 1981; Lucchi et al., 2013a; Albert et al., 2017).

The most prominent of these deposits are the brownish ash deposits known as “Brown Tuffs,” which originate from Vulcano and are divided into three macro-units: the Lower (81-56 ka) and Intermediate (56-24 ka), belonging to the Pianoconte formation, and the Upper Brown Tuffs (24-6 ka), belonging to the Piano di Grotta dei Rossi formation (Lucchi et al., 2008, 2013a; Meschiari et al., 2020).

Other important markers for correlations are the Rocce di Barcone formation (Grey Porri Tuffs; 70-67 ka, Sulpizio et al., 2016) and Punta Fontanelle formation (Lower Pollara Tuffs; 27.5 cal ka) from Salina.

All the rhyolitic volcanic units on Lipari are stratigraphically located above the Ischia Tephra, which is the distal equivalent of the Monte Epomeo Green Tuff of Ischia (Tomlinson et al., 2014), dated at 56.1 ± 1.0 ka (Giaccio et al., 2017). The distinctive lithostratigraphic features and age information of these units are hereafter synthetically described, according to the stratigraphic order established from previous works and still unpublished studies. Starting from the oldest, they are the Punta del Perciato, Falcone, Monte Guardia, Monte Giardina, Punta San Giuseppe, Castello, Capo Rosso, Vallone Canneto dentro, Vallone del Gabellotto, Pomiciazzo, Monte Pilato, Forgia Vecchia, Lami and Rocche Rosse formations.

3.1 Punta del Perciato Formation

The oldest rhyolitic products on Lipari are represented by the remnants of two endogenous NNW-SSE-aligned lava domes exposed along the coastal cliff of Scogliera sotto il Monte and the isolated rocks of le Formiche, Pietralunga and Pietra Menalda in the southern sector of the island. These domes have thick blocky upper carapaces and show typical internal flow foliation of interlayered rhyolitic, vesicular and (minor) vitreous lava (Fig. 3). Lava is scarcely porphyritic (less than 5 vol%) with phenocrysts of K-feldspar, plagioclase and hornblende, minor biotite, magnetite and accessories (Gioncada et al., 2005).

The domes are covered by a whitish pumiceous pyroclastic succession (pe) composed of massive lithic-rich pyroclastic-breccias, in near-vent areas, passing to stratified lapilli-tuffs and tuffs towards distal areas. Scarce, frequently brecciated obsidian fragments (up to a few cms in diameter) are present within these pyroclastic deposits, particularly in the vent area near to Punta di Iacopo.

This unit is undated directly, although its stratigraphic interval can be constrained between c. 56 ka (age of the underlying Ischia Tephra) and 43-40 ka (age of the successive Falcone domes). This gives an approximate age interval to the onset of rhyolitic magmatism on Lipari.

Figure 3. Spiaggia di Valle Muria (Punta di Levante). Punta del Perciato formation: internal flow foliation of rhyolitic, vesicular and (minor) vitreous lava dome. Scale: the hammer in the circle.

3.2 Falcone Formation

This unit is represented by a whitish pumiceous pyroclastic succession (fa) composed of massive, lithic-rich tuff-breccias passing laterally (from south to north) to cross-stratified lapilli-tuffs and tuffs (Fig. 4A). These deposits have maximum thickness of 15 m along the south-western coasts, whereas dm-thick layers are widespread in the central-southern sectors of the island. Obsidian fragments (Fig. 4B) with a diameter in the range of 5-10 cm are present in the outcrops along the coastal cliff of Scogliera sotto il Monte, south Lipari, whereas they are less abundant and smaller in size away from the vent areas. This pyroclastic succession is covered by the large, NNW-SSE-aligned endogenous lava domes of Falcone, Capparo and Capistello. These have typical blocky carapaces and well-developed flow foliation of interlayered rhyolitic, vesicular and (minor) vitreous lava. Lava is scarcely porphyritic with the same phenocrysts of the Punta del Perciato domes (Gioncada et al., 2005), and abundant xenoliths in places. The Falcone domes crop out in the southern sector of the island, and are presently deeply eroded, weathered and displaced by volcano-tectonic collapses. They are K-Ar dated to 43-40 ka (Gillot, 1987; Crisci et al., 1991; Leocat, 2011).

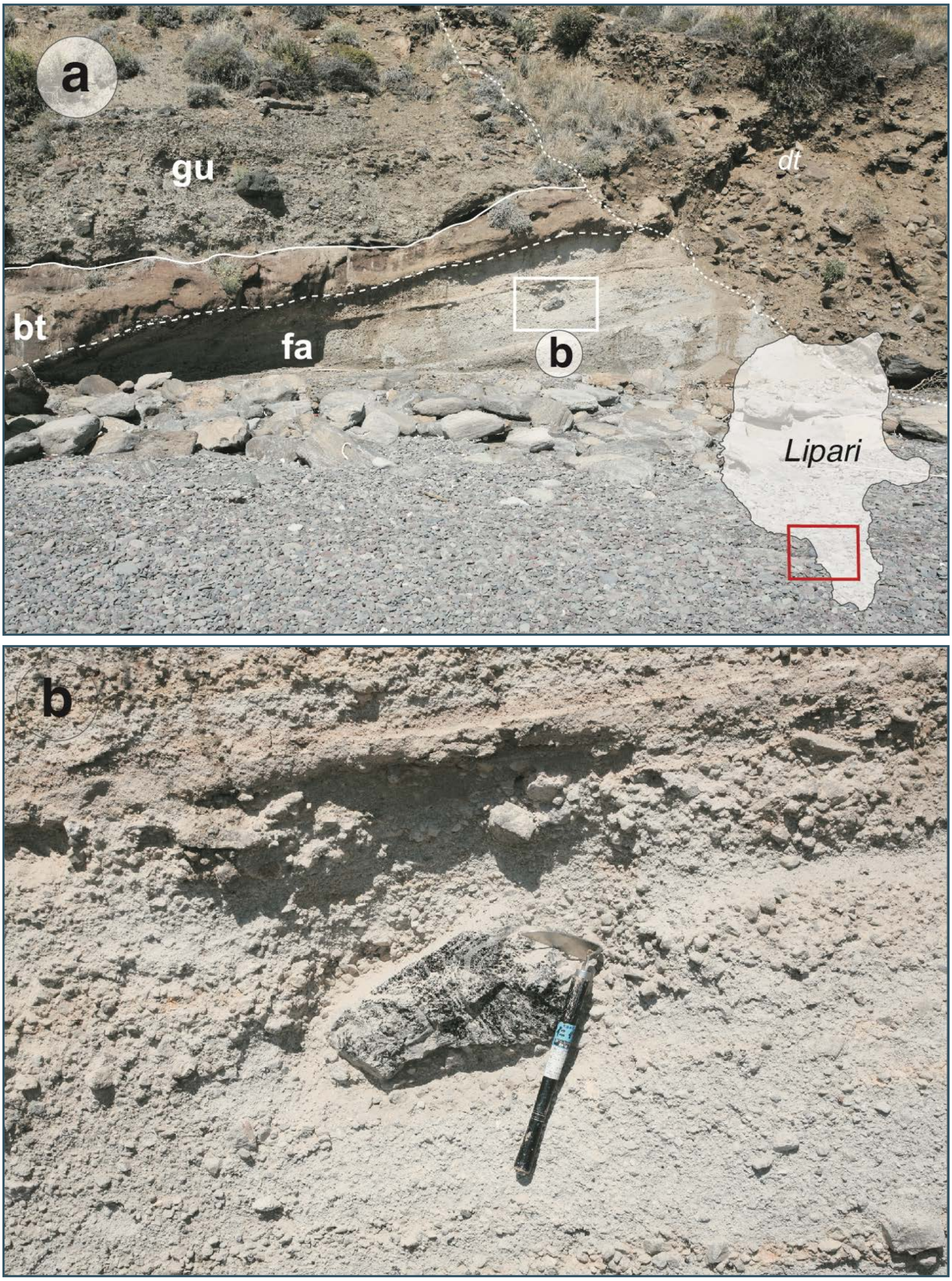

Figure 4. Rhyolite volcanic products of Falcone formation (EE 7) in the SW sector of the island. (a) outcrop of Falcone formation (fa) and stratigraphic relationships with the overlying deposits of Brown tuff (bt) and Monte Guardia formation (gu). (b) block of fractured obsidian within the pyroclastic succession of Falcone formation (fa).

3.3 Monte Guardia Formation

This is a thick and widespread pumiceous pyroclastic succession (Crisci et al., 1983; De Rosa and Sheridan, 1983; Colella and Hiscott, 1997; De Rosa et al., 2003a; Forni et al., 2013), cropping out across the whole island of Lipari with distal layers recognized over most of the Aeolian archipelago (Lucchi et al., 2013a). It is composed of lithic-rich tuff-breccias, in near-vent areas, passing laterally (from south to north) to planar and cross-stratified lapilli-tuffs and massive tuffs. Highly vesicular, scarcely porphyritic, white pumices are associated to moderately vesicular latitic grey pumices and banded pumices (De Rosa et al., 2003a), with abundant lithic clasts in the near-vent breccia layers (Figs 5A, B). All the pumice types are porphyritic. A conspicuous amount of obsidian fragments (mostly in the range of 1-10 cm) is present in most of the outcrops (Figs. 5C, D), although the largest clasts are frequently deeply brecciated. Small lapilli and coarse ash of obsidian are present also in the distal fall layers recognized on Panarea and Vulcano. The Monte Guardia succession has a maximum thickness up to 50 m in a quarry near to Capistello, whereas metric-thick layers are widely distributed across most of the island of Lipari. The age of Monte Guardia is of 27-26 ka (calibrated time interval), as derived from the radiocarbon calibrated ages of the Brown Tuffs at the base and the top of the corresponding pumiceous deposits (Meschiari et al., 2020).

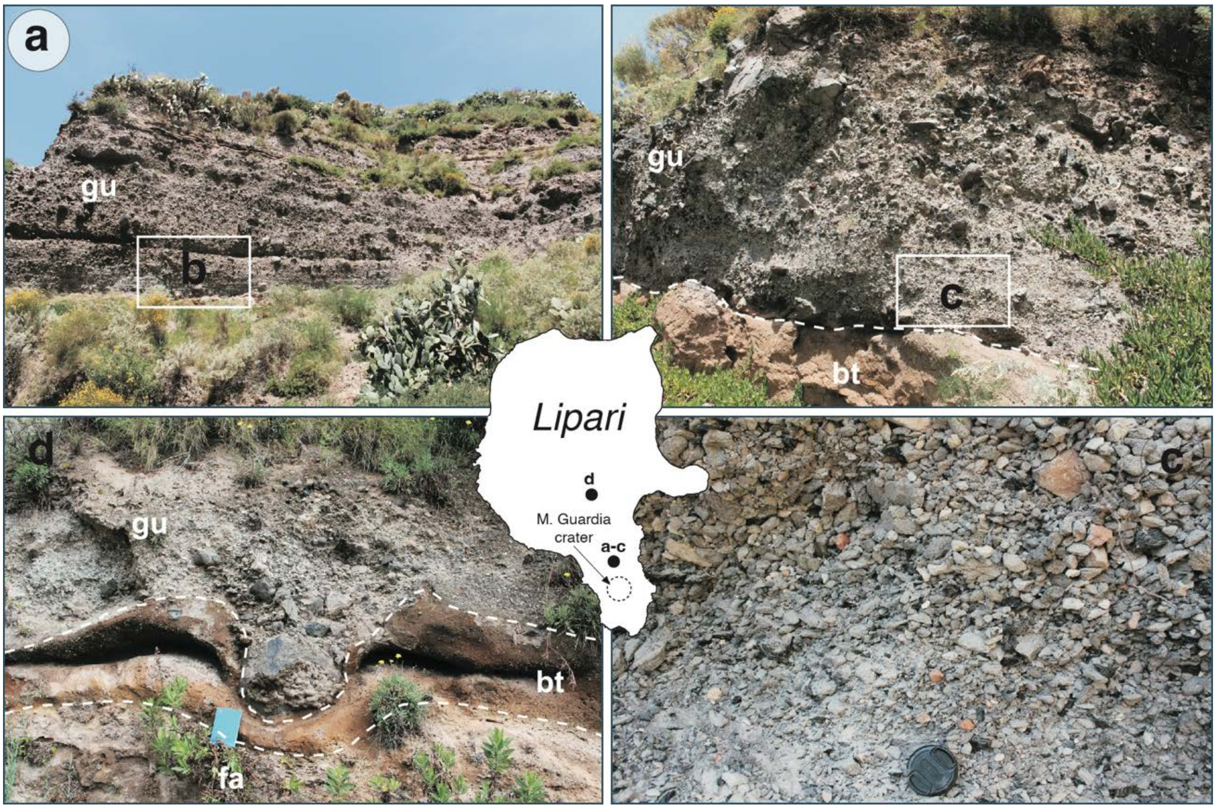

Figure 5. Rhyolite volcanic products of Monte Guardia formation (EE 8). (a-c) outcrops in the proximal area of Valle Muria where the pyroclastic deposits of the Monte Guardia formation (gu) are visible. (d) Photograph of Monte Guardia pyroclastic succession about a few kilometers from the source area (on the slope of M.S. Angelo). fa = Falcone formation; bt = Brown Tuff; gu = Monte Guardia formation.

3.4 Monte Giardina Formation

This unit includes the NNW-SSE-aligned endogenous lava domes of S. Lazzaro, M. Guardia and M. Giardina that occupy most of the southern sector of the island of Lipari. The domes are spectacularly exposed with subcircular shape and diameter of 450-850 m and consist of a subvertical lava front (up to 100 m thick) encircled by a steep talus slope deposit. The inner portions are characterized by well-developed flow foliation with interlayered lithic rhyolite, vesicular and vitreous lava. Lava is scarcely porphyritic with the same phenocryst assemblage of the previous domes (Gioncada et al., 2005). We assume that the Monte Giardina domes erupted immediately after the Monte Guardia pyroclastic succession based on the absence of erosional unconformities between these deposits.

A maar crater is formed on the summit of the Monte Giardina lava dome by massive tuff-breccias consisting of rhyolite lava clasts similar to the underlying dome, with no fresh juvenile clasts.

3.5 Punta S. Giuseppe Formation

Three NNW-SSE-aligned, endogenous lava domes are exposed in the southern sector of Lipari. They are subcircular to elliptical, with diameter in the range 200-800 m, and show well developed rampart structures and internal flow foliation with interlayered bands of lithic rhyolite, vesicular and vitreous lava. Lava is almost aphyric, but it is characterized by abundant mafic enclaves and xenocrysts. The southernmost and bigger dome is cut by a subcircular collapse that is partially filled by a small secondary dome.

The Punta S. Giuseppe domes are recognized in the same stratigraphic window of the Monte Giardina ones, between the Monte Guardia succession (27-24 ka) and below the Upper Brown Tuffs (24-6 ka), and are thus considered as contemporaneous, being erupted from two parallel NNW-SSE eruptive fissures.

3.6 Castello Formation

North-south-aligned, small endogenous lava domes discontinuously crop out in the intensely urbanized area of the Lipari village, showing well-developed flow foliation of interlayered rhyolite, vesicular and vitreous lava in the coastal outcrops. Lava is always aphyric. The summit of the bigger dome is occupied by the archaeological area and the acropolis called the Castle of Lipari.

The Castello domes are not dated directly, but they are mostly recognized above the Upper Brown Tuffs, thus being younger than the previous Monte Giardina and Punta S. Giuseppe domes.

3.7 Vallone Canneto dentro Formation

A squat endogenous lava dome (50 m thick and 300 m large) is exposed in the area of Vallone Canneto Dentro (Fig. 6A), showing well-developed flow foliation of interlayered (aphyric) rhyolite, vesicular and vitreous lava, rampart structures and a blocky and rough upper surface.

The dome is encircled by a 4 m thick pyroclastic succession (Figs. 6A, B) consisting of massive to stratified, pumiceous tuff-breccias with interlayered thinly bedded tuff beds, which crop out widely along the sides of the valley (Fig. 6B). This near-vent succession includes abundant lithics and angular (glassy) obsidian fragments with a diameter in the range of 5-15 cm.

The Vallone Canneto dentro pyroclastics and dome are currently undated, but they are stratigraphically well defined above most of the Upper Brown Tuffs, radiocarbon dated to 24-20 cal ka (Lucchi et al., 2008; Meschiari et al., 2020), and below the Vallone del Gabellotto marker bed (8.7-8.4 cal ka; Siani et al., 2004). No erosional unconformities and palaeosols are recognized between the Vallone Canneto dentro and Vallone del Gabellotto pyroclastic successions, which suggests that the relative eruptions occurred close in time.

3.8 Capo Rosso Formation

These are three north-south-aligned endogenous lava domes with well-developed flow foliation and rampart structures cropping out along the coastal cliff in the north-eastern sector of Lipari. They are characterized by strong hydrothermal alteration and the original characters of the lithotype are barely visible.

Currently undated, the Capo Rosso domes are stratigraphically defined below the Vallone del Gabellotto marker bed (8.7-8.4 ka), with the contact marked by a deep erosional surface that is evidence of a prolonged quiescence period between the two eruptions.

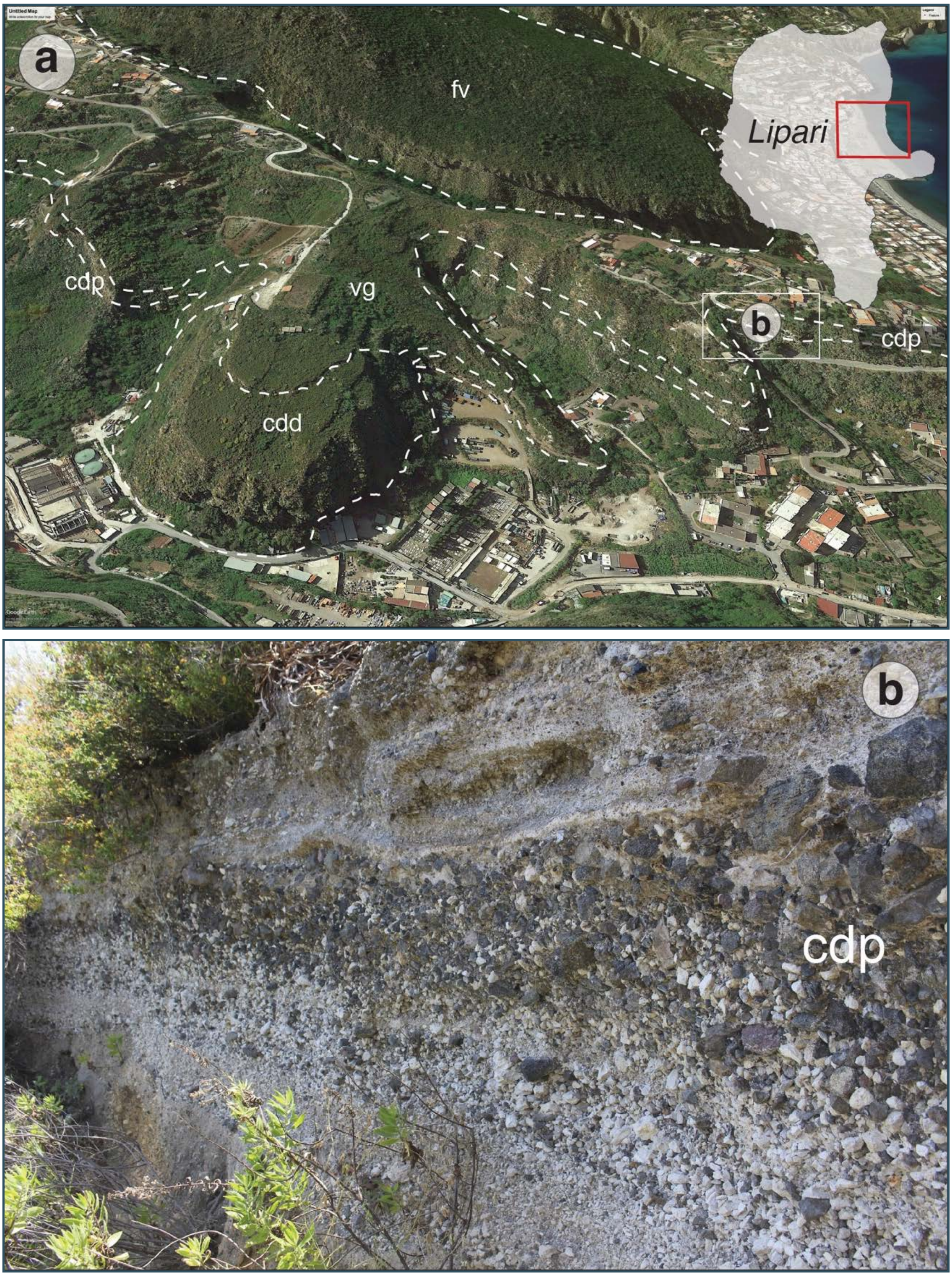

Figure 6. Rhyolite volcanic products of central sector of Lipari. (a) Google Earth© photograph of Canneto dentro area indicating the stratigraphic relationships between the main formations of Eruptive Epochs 8 and 9; cdp = pyroclastic succession; cdd = dome); vg = Vallone del Gabellotto formation; fv = Forgia Vecchia formation. (b) outcrop of Canneto dentro cdp: pumiceous pyroclastic succession with black obsidian clasts.

3.9 Vallone del Gabellotto Formation

This is a thick pumiceous pyroclastic succession widely distributed across the whole central-northern sectors of Lipari (Figs. 2 and 7A), with spectacular outcrops along the steep walls of the Vallone del Gabellotto gorge (up to 130 m thick; Fig. 7B), and around Vallone Fiume Bianco. The main deposit consists of massive to stratified tuff-breccias, lapilli-tuffs and tuffs composed of dense to highly vesicular aphyric pumice with a variable content of lithics and angular (glassy) obsidian clasts with a diameter in the range of 1-20 cm. Distal tephra layers are recognized on Panarea and Vulcano (Lucchi et al., 2013a) and even in Adriatic and Tyrrhenian deep-sea cores, where the corresponding E-1 tephra layer has been radiocarbon dated to 8.7-8.4 cal ka (Siani et al., 2004), which is the assumed age for the Vallone del Gabellotto explosive eruption.

3.10 Pomiciazzo Formation

This large obsidian-rich lava coulee (up to 30 m thick) forms three c. 450 m-large lava lobes along the north-eastern coastal sector of Lipari to the north of Canneto, extending down the submarine slope for a total length of >4.5 km (Gamberi and Marani, 1997). The coulee is currently largely covered by younger deposits, but its inner core is best exposed along the steep wall of the Vallone del Gabellotto Gorge (Fig. 8), showing well-developed flow foliation of interlayered lithic rhyolite and vesicular lava with large portions of glassy (to spherulitic) obsidian.

We assume that the Pomiciazzo coulee erupted immediately after the Vallone del Gabellotto pumice succession because no erosional unconformity or paleosoil are recognized between them. Accordingly, the fission track age of 8.6 ka provided by Wagner et al. (1976) and Arias et al. (1986) is considered as the most probable because it is perfectly consistent with the age of the Vallone del Gabellotto unit (8.7-8.4 ka), even if other ages of 11-7 ka are available (Bigazzi and Bonadonna, 1973; Bigazzi et al., 2003).

3.11 Sciarra dell'Arena Formation

This unit is mostly represented by a thick pumice succession that builds up the Monte Pilato pumice cone (c. 350 m high) in the north-eastern sector of Lipari (Figs. 7A and 8). This succession is widely distributed and mantles the topography above the Vallone del Gabellotto pumice succession with the contact marked by a thick (up to 0.5 m) reddish, humic-rich, laterally persistent paleosol. The Monte Pilato succession is spectacularly exposed on the subvertical cliffs left by the pumice quarries active until the 1990s that cut the flanks of the cone near Porticello and Acquacalda, with a maximum thickness of c. 150 m that rapidly decreases away from the source on distances of c. 2.5 km from the vent, whilst distal tephra layers are recognized on Panarea, Stromboli and Vulcano (Lucchi et al., 2013a). The succession is composed of massive to stratified, ash-supported lapilli-tuffs and tuffs interlayered with beds of well sorted clast-supported lapilli. These deposits mostly consist of whitish, highly vesicular pumice, with abundant lithic clasts of andesitic and scarce rhyolitic lava and minor obsidian clasts (increasing towards the top of the succession).

Remnants of an obsidian-rich lava coulee are discontinuously recognized along the lowered, north-eastern side of the Monte Pilato crater, even if dense vegetation and difficult outcrop conditions currently do not make it possible to reach the outcrops.

The Monte Pilato eruption is dated to 776 CE based on the calibrated 14C age of carbonized plant material embedded within the base of the pyroclastic succession (Keller, 2002), which is fully consistent with the radiocarbon age of 780-785 CE by Keller (1970). This age is consistent with the occurrence of the Monte Pilato deposits above Greco-Roman ruins (dated up to 4-5th centuries CE) in the archaeological area of Contrada Diana in Lipari (Keller, 1970) and above Late Antique Butrint (from late 4th to late 6th century CE) archaeological excavations in Albania (Bescoby et al., 2008). The age of 776 CE is also consistent with the historical report by monk Gregorius of explosive activity on Lipari in 787 CE (cited by Keller, 2002). Other historical reports are more questionable (c.f. Bernabò-Brea, 1978; Pichler, 1980).

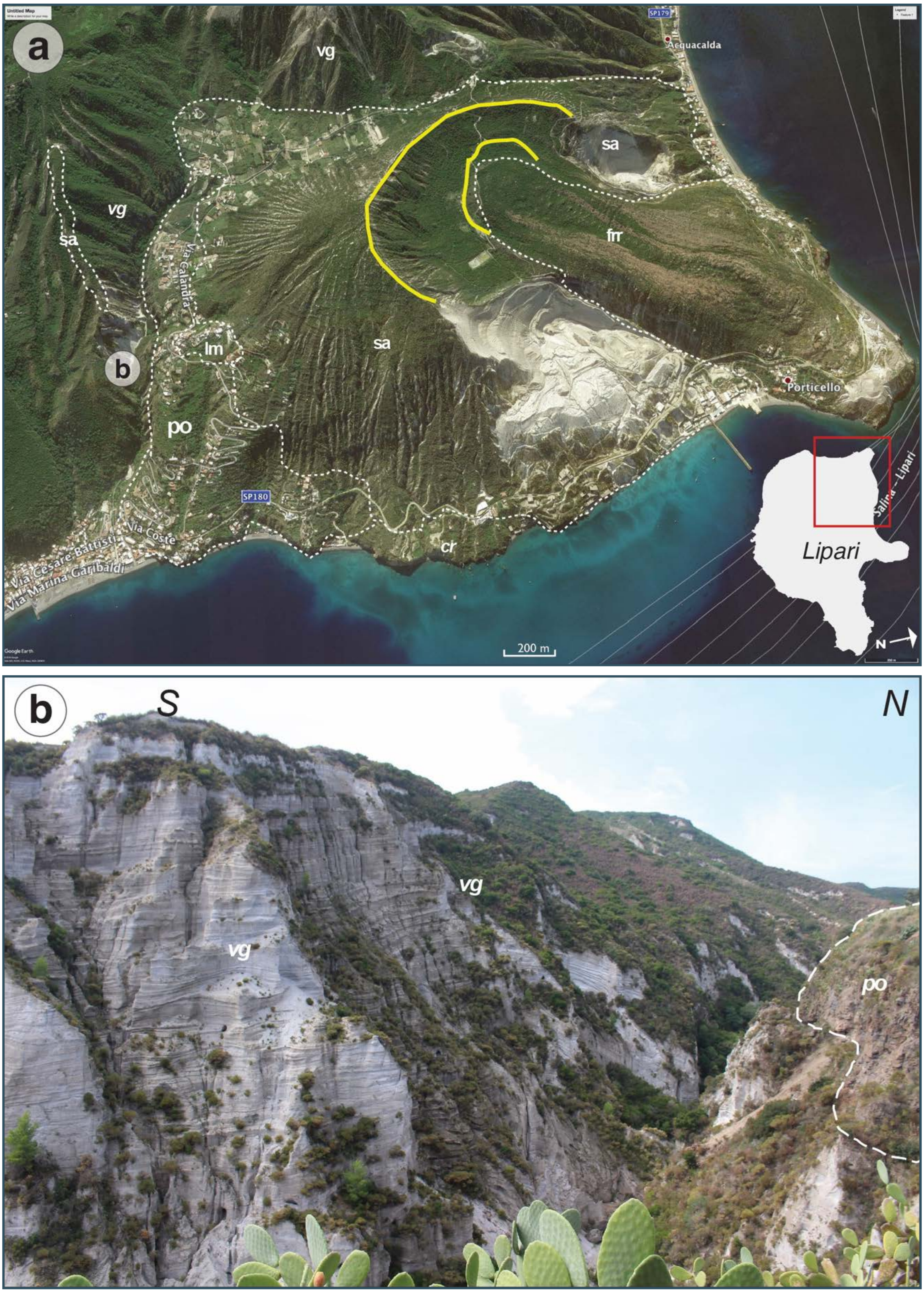

Figure 7. Rhyolite volcanic products of the north-eastern sector of Lipari. (a) Google Earth© photograph of NE sector of the island with the main stratigraphic units of Eruptive Epoch 9; cr = Capo Rosso formation; vg = Vallone del Gabellotto formation; po = Pomiciazzo formation; sa = Sciarra dell'Arena formation; frr = Fossa delle Rocche Rosse formation. (b) The Vallone del Gabellotto formation (pyroclastic succession) is best exposed on the south side of the Vallone del Gabellotto gorge (near to the source area), while the Pomiciazzo coulee outcrops in the upper part of the northern wall; vg = Vallone del Gabellotto formation; po = Pomiciazzo formation. Dashed lines = boundaries between formations; thick lines = crater.

Figure 8. Pomiciazzo coulee (seen from the south) extensively covered by the most recent deposits of the Lami and Sciarra dell'Arena formations (Monte Pilato eruption). vg = Vallone del Gabellotto formation; po = Pomiciazzo formation; sa = Sciarra dell'Arena formation.

3.12 Forgia Vecchia Formation

This is a bilobate, tongue-like (30 m thick) obsidian-rich lava coulee hanging behind the Canneto village (Fig. 6A), showing the typical blocky and cracked surface and internal flow foliation with interlayered lithic rhyolite and vesicular lava and sheared to glassy obsidian. This coulee is originated from a low-profile crater near the village of Pirrera, which is constructed by a 5 m thick pumiceous pyroclastic succession consisting of massive to stratified, ash-supported tuff-breccias and lapilli-tuffs and clast-supported lapilli beds. These deposits are composed of whitish to grey, highly vesicular pumice and lithics of andesite lavas, with grey and black obsidian clasts (up to 40 cm large) and breadcrusted bombs more abundant towards the top of the succession.

The Forgia Vecchia coulee has been recently robustly dated to the Late Middle Ages (1242-1306 CE) by means of combined radiocarbon and paleomagnetic ages (Pistolesi et al., 2021), thus being younger than the Monte Pilato eruption. This new age attribution is substantially younger than the previous fission-track age of 1.6 ka by Bigazzi and Bonadonna (1973).

3.13 Lami Formation

This unit is a pumiceous pyroclastic succession cropping out along the southern flank of the Monte Pilato cone (Fig. 7A), where it forms a low-profile crater near the village of Lami. It is a massive to stratified deposit composed of well sorted, clast-supported lapilli and bombs and minor ash-supported lapilli-tuffs, characterized by a distinctive m-thick layer of densely welded and flattened, highly vesicular pumice at the top of the succession ('pipernoid pumice deposits'; Pichler, 1980). The deposit is made up of whitish to grey, highly vesicular to frothy pumice together with rhyolite lava lithics and abundant grey to black (and banded) obsidian fragments (diameter in the range 5-10 cm). Peculiar transitional pumice-obsidian clasts are present (Davì et al., 2011), as well as similar Pele's tear obsidian pyroclasts, and breadcrusted obsidian bombs, with variably fractured and healed glassy rinds (Cabrera et al., 2011, 2015).

The Lami eruption is dated to the Late Middle Ages (700 years BP) based on a fission track age by Bigazzi et al. (2003), which was recently confirmed by paleomagnetic dating to 1253-1316 CE by Pistolesi et al. (2021).

3.14 Fossa delle Rocche Rosse Formation

This unit includes the renowned Rocche Rosse obsidian-rich lava coulee located at the northeastern corner of the island of Lipari between Porticello and Acquacalda (Fig. 7A). It is a lobate, tongue-like (up to 60 m thick) coulee with well-developed rampart structures, blocky and cracked surface and internal flow foliation of interlayered glassy obsidian, lithic rhyolite and vesicular lava (Shields et al., 2016; Bullock et al., 2018). Large portions of glassy obsidian are recognized, although it is largely characterized by devitrification textures (e.g. perlite and spherulites) (Gimeno, 2003; Clay et al., 2013; Bullock et al., 2017).

The Rocche Rosse coulee originated from a low-profile tephra ring, coalescent with the older Monte Pilato crater, which is constructed by a m-thick pyroclastic succession composed of medium to thick beds of lithic-rich, pumiceous lapilli-tuffs with a distinctive m-thick layer of dark-colored, welded, highly vesicular juvenile fragments. This deposit mostly consists of whitish to grey, moderately vesicular to dense pumice and grey to black obsidians, with rhyolitic lava lithic clasts (and minor andesites).

The Rocche Rosse eruption is dated to the Late Middle Ages (1220 CE) based on the archaeomagnetic datings by Tanguy et al. (2003) and Arrighi et al. (2006), and more recently confirmed by paleomagnetic dating to the 1243-1304 CE by Pistolesi et al. (2021): this age attribution, which is substantially younger than the previous fission track age of 1.4 ka by Bigazzi and Bonadonna (1973), fits with the evidence that the Rocche Rosse pyroclastic deposits crop out above an erosional unconformity representing a period of quiescence after the M. Pilato activity (dated to 776 CE).

4. Discussion

The lithostratigraphic features of rhyolitic volcanic units erupted on Lipari during the last ~50 ka, and the content and characteristics of the obsidian they carry, are hereafter discussed to identify main obsidian subsources on the island. To do this, the following characters must be considered: i) age of the eruptions producing obsidian; ii) quantity of obsidian they carry; iii) quality of the obsidian (in terms of physical and chemical properties); iv) conditions of exploitation; v) distribution of the outcrops of exploitable obsidian.

In most of the available literature (Bigazzi et al., 2005; Tykot et al., 2006; Freund et al., 2017; Freund, 2018; Tykot, 2019) it is pointed out that Lipari's obsidian during the Neolithic was exploited from the pumiceous pyroclastic successions of Vallone del Gabellotto and Vallone Canneto dentro, as particularly suggested by the chemical compatibility with numerous artefacts from archaeological sites dating from the Neolithic, Copper, and Bronze Ages (Tykot et al., 2013). This is in general agreement with the lithostratigraphic review that we presented here. The eruption ages of the Vallone Canneto dentro (stratigraphically defined between 20 and 8 ka) and Vallone del Gabellotto pyroclastics (8.7-8.4 ka) are in fact compatible with the time interval of long-term exploitation of the Lipari's obsidian which occurred from the sixth to the second millennia BC. Both these units contain abundant obsidian clasts with diameters up to tens of centimetres (Figs. 6B, 9 and 10). The black glassy obsidian carried by these units has a perfectly vitreous, crystal- and vesicle-free structure and conchoidal fracture which facilitates its use as raw material (Donato et al., 2018). Between the two, the Vallone del Gabellotto is the volumetrically most important deposit, with outcrops of obsidian-rich breccia deposits at the base of the succession along the Vallone del Gabellotto gorge and on the summit of the Monterosa cape (Fig. 9). Unfortunately, the outcrops at the base of Vallone del Gabellotto, well documented by Tykot (2019) are no longer easily accessible due to intense vegetation and interventions to manage debris discharge. The rest of the succession is exposed in thick and laterally extensive outcrops along the walls of the Vallone del Gabellotto Gorge and in the flattish area of Vallone Fiume Bianco in the internal area of Lipari, but they are characterized by a limited amount of (outsize) obsidian fragments. The dominant role of Vallone del Gabellotto as an obsidian subsource is confirmed by the chemical compositions of most of the

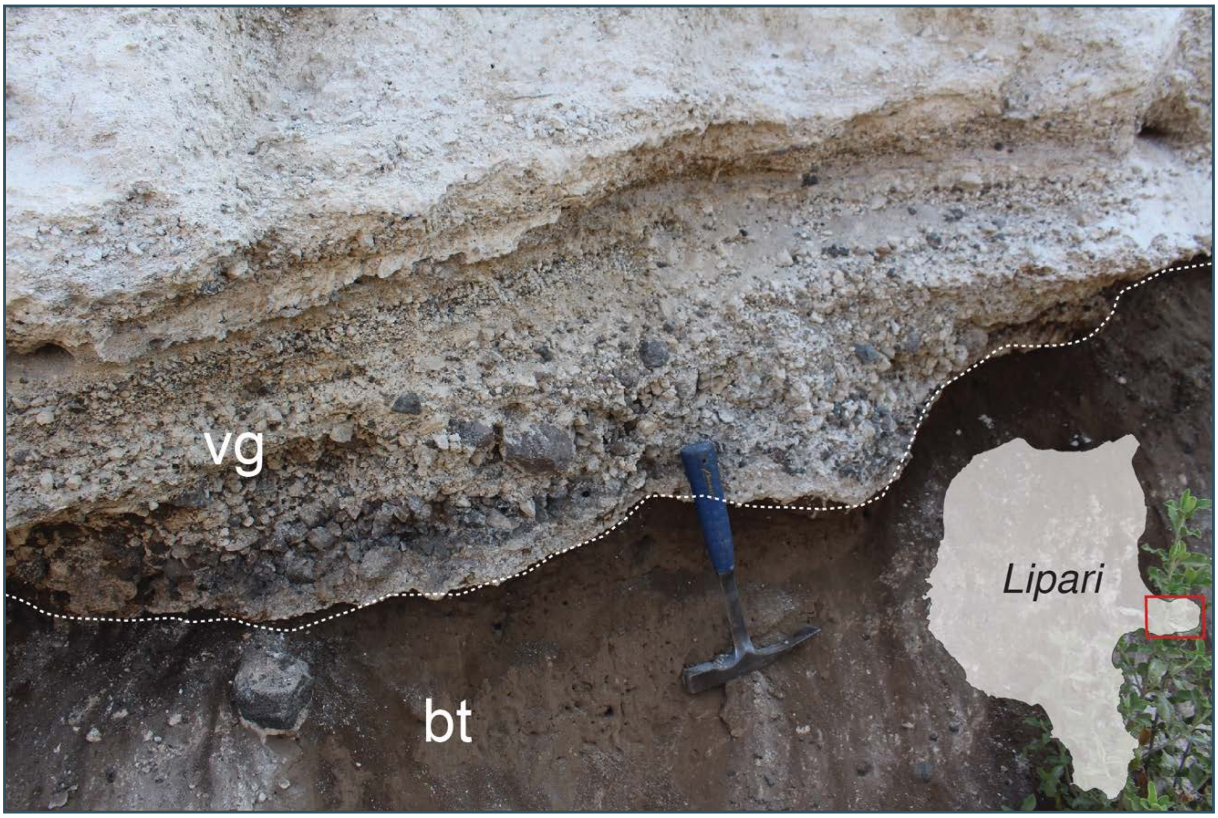

Figure 9. Outcrop of Vallone del Gabellotto formation (vg) on the summit of the Monterosa cape. In evidence the large amount of black obsidian clasts within the whitish pumiceous pyroclastic succession. bt = Brown Tuff.

archaeological findings in Neolithic sites outside Lipari (Tykot, 2019). Vallone Canneto dentro was only a minor subsource, with some outcrops of obsidian-rich pyroclastic deposits encircling the dome to the south of Canneto.

The rhyolitic volcanic units erupted during the Middle Ages (Monte Pilato, Forgia Vecchia, Lami, Rocche Rosse), despite containing large quantities of glassy (high quality) obsidian, are too young to have been of archaeological importance. On the other hand, the rhyolitic volcanic units erupted in the time interval 50-20 ka mostly in the southern sector of Lipari are not considered suitable sources of exploitable obsidian (e.g. Bigazzi et al., 2005). The older Punta del Perciato and Falcone pyroclastic successions contain a limited amount of obsidian fragments, which are generally deeply brecciated (particularly in Falcone; Fig. 4), and the near-vent facies of these deposits, expected to have a high amount of lithic clasts and obsidian, are generally not exposed due to the cover of more recent deposits. The Monte Guardia unit, instead, is characterized by several outcrops of a basal, lithic-rich pyroclastic breccia that contains abundant glassy obsidian clasts with diameters in the range 2-20 cm, only in some cases fractured or brecciated (Fig. 5). Outcrops of this breccia are visible along the valley of Valle Muria and in the areas of Capistello and Falcone, and along the southern flanks of the Monte S. Angelo stratocone in the central sector of Lipari (Fig. 5D). Despite the Monte Guardia pyroclastic succession is spread over the entire island of Lipari and contains numerous obsidian clasts up to decimetric diameters (mainly in the most proximal outcrops of Capistello), no artefacts referable to this source have ever been found among the thousands of samples analyzed in different Neolithic archaeological assemblages (Tykot, 2019). This is likely due to poor workability of obsidian of the Monte Guardia succession, and the difficulty in obtaining perfect conchoidal surfaces to produce stone tools, because of its frequent and pervasive brecciation. The Monte Guardia succession also includes a minor amount of grey obsidian characterized by small vesicles and nano-crystals that is considered of less quality for exploitation (Donato et al., 2018). Further, the endogenous rhyolitic lava domes recurrently erupted in the southern (Punta del Perciato, Falcone, Monte Giardina, Punta S. Giuseppe), central (Castello) and north-eastern sectors (Capo Rosso) of Lipari do not show pure obsidian portions, apart from vitreous bands in the internal flow foliation structures, as typical of their growth style (Calder et al., 2015). These considerations can also be applied to the Vallone Canneto dentro lava dome, linked to the pyroclastic unit with the same name, which is not considered a suitable obsidian subsource on Lipari (Freund, 2018).

The case of the Pomiciazzo coulee, erupted immediately after the Vallone del Gabellotto unit, is somewhat different, because it is a typical example of a rhyolitic lava coulee with large portions of black, glassy obsidian (similar to the younger Rocche Rosse coulee), and its age (8.6 ka) is perfectly compatible with the time interval of main exploitation of obsidian during the Neolithic. In this sense, it is necessary to discuss why pyroclastic deposits are generally considered preferred sources of obsidian compared to lava domes and coulees (e.g. Freund, 2018). We can reasonably assume that obsidian clasts can be extracted more easily from pyroclastic deposits, particularly those unwelded and poorly coherent like the Vallone Canneto dentro and Vallone del Gabellotto, because they are found in fragments of adequate size to be worked (and transported) as raw material. Even now, it is frequent to find angular glassy obsidian clasts with conchoidal fractures within these pyroclastic deposits (Fig. 10) because of the explosive fragmentation process. On the other hand, it must have been complicated for Neolithic populations to take obsidian blocks from the Pomiciazzo coulee with the tools of that time, before the technology of metal took over (Cavalier, 1979), even if ground-stone axes could have been used to easily remove some large pieces of obsidian from the Pomiciazzo coulee. However, we note that the current outcrops of the Pomiciazzo coulee are only a small part of its original areal extension, because of the wide cover of the more recent Monte Pilato pyroclastic deposits (Figs. 7 and 8). At the time of its potential use in the Neolithic, the surface of the Pomiciazzo coulee had to be entirely exposed along the coastal sector to the north of Canneto, in a manner very similar to what currently happens for the Rocche Rosse coulee, which has similar lithofacies characteristics. It is clearly evident that at the present time numerous blocks of obsidian emerge from the surface of the Rocche Rosse coulee, and it is not very complicated to extract fragments to be used as raw material. Similarly, pieces of obsidian could have been available and exploited by Neolithic people on the surface and flanks of the Pomiciazzo coulee. To confirm this, we note that some prehistoric (Neolithic) obsidian quarries were discovered during the construction of the Canneto-Lami road in 1969 (Keller, 1970; Cavalier, 1979, 1997), which is cut into the surface of the Pomiciazzo coulee to the north of the Vallone del Gabellotto gorge. This could also indicate that the Pomiciazzo coulee may have been exploited during the Neolithic for the extraction of obsidian raw material. However, no data are currently available regarding such exploitation in the archaeological obsidians of the Mediterranean area. In addition, there are presently no

Figure 10. Vallone del Gabellotto gorge. Obsidian block emerging from the pyroclastic succession of Vallone del Gabellotto formation.

detailed geochemical data that would allow the Pomiciazzo subsource to be distinguished from others. An accurate geochemical characterization of the Pomiciazzo coulee could be useful for the future attribution of Neolithic obsidians to this subsource.

5. Conclusions

A review of the lithostratigraphic features of the rhyolitic obsidian-bearing volcanic units erupted on Lipari during the last ~50 ka allows identification of the main subsources of obsidian raw materials during the Neolithic (between 6000 and 2000 BC). The main outcomes of this work are the following:

- the pyroclastic deposits of Vallone del Gabellotto (8.7-8.4 cal ka) are the main obsidian subsource on Lipari due to compatible age of eruption, volume and areal distribution of products and abundance of high-quality black, glassy obsidian. The Vallone Canneto dentro pyroclastics (stratigraphically dated between 20-8 ka) are a minor subsource (consistent with what was suggested by previous literature);
- the volcanic units of Monte Pilato, Forgia Vecchia, Lami and Rocche Rosse, despite carrying high amounts of glassy obsidian, are all related to eruptions that occurred during the Middle Ages, thus being younger than the time interval of obsidian exploitation during the Neolithic, Copper and Bronze ages;
- the Monte Guardia pyroclastic succession (27-26 ka, calibrated time interval) is characterized by a large number of outcrops of a basal, lithic-rich pyroclastic breccia (mainly in the proximal outcrops of the Capistello quarry) that could have been a potential subsource of exploitable obsidian, although the analysis of numerous artifacts from sites of the Mediterranean area has revealed no attribution to it likely due to pervasive brecciation and difficult workability.

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