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RESEARCH ARTICLE

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Eruptive dynamics and caldera collapse during the Onano eruption, Vulsini, Italy

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Abstract The Onano explosive eruption of the Latera Volcanic Complex (Vulsini Volcanoes, Quaternary potassic Roman Comagmatic Region, Italy) provides an interesting example of multiple changes of eruptive style that were concomitant with a late phase of collapse of the polygenetic Latera Caldera. This paper reports a reconstruction of the event based on field analysis, laboratory studies of grain size and density of juvenile clasts, and reinterpretation of available subsurface geology data. The Onano eruption took place in a structurally weak area, corresponding to a carbonate substrate high bordered by the pre-existing Latera caldera and Bolsena volcano-tectonic depression, which controlled the ascent and eruption of a shoshonitic-phonotephritic magma through intersecting rim fault systems. Temporal changes of magma vesiculation, fragmentation and discharge rate, and consequent eruptive dynamics, were strongly controlled by pressure evolution in the magma chamber and changing vent geometry. Initially, pumice-rich pyroclastic flows were emplaced, followed by spatter- and lithic-rich flows and fallout from energetic fire-fountaining. The decline of magma pressure due to the partial evacuation of the magma chamber induced trapdoor collapse of the chamber roof, which involved part of the pre-existing caldera and external volcano slopes and eventually led to the present-day caldera. The widening of the vent system and the emplacement of the main pyroclastic flow and associated co-ignimbrite lag breccia marked the eruption climax. A sudden drop of the confining pressure, which is attributed to a pseudo-rigid behaviour of the magma chamber wall rocks during a phase of rapid magma drainage, led to extensive magma vesiculation and fragmentation. The disruption of the magma chamber roof and waning magma pressure in the late eruption stage favoured the explosive interaction of residual magma with groundwater from the confined carbonate aquifer. Pulsating hydrostatic and magma pressures produced alternating hydromagmatic pyroclastic surges, strombolian fallout and spatter flows.

Keywords Explosive eruption · Caldera · Vesiculation · Lithic-rich breccia · Spatter flow · Potassic volcanism · Vulsini

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Introduction

As it is widely reported in the volcanological literature, major explosive eruptions often occur as causes and/or effects of caldera collapses (e.g., Smith and Bailey 1968; Druitt and Sparks 1984; Heiken and McCoy 1984; Scandone 1990). Many studies have focused on specific facies associations of pyroclastic deposits that can be considered as indicative of caldera-forming events. Commonly, volcanic successions in caldera settings comprise large-volume ash and pumice flow deposits, spatter- and lithic-rich breccias and pyroclastic surge deposits of hydromagmatic origin, which are often associated even in single eruptive events (e.g., Druitt and Sparks 1982; Druitt and Bacon 1986; Mellors and Sparks 1991; Perrotta and Scarpati 1994; Rosi et al. 1996). In particular, co-ignimbrite lag breccias (Walker 1985) are interpreted to mark the onset of caldera collapse, whereas hydromagmatic deposits may form during late eruptive stages following disruption of the top of the magma chamber (e.g., Sigurdsson et al. 1985).

In reconstructing the evolution of young calderas, their relatively well preserved topographic appearance may be often misleading in interpreting their subsurface structure (cf. Kokelaar and Branney 1999). Moreover, the detection of structural elements may prove difficult in volcaniclastic terrains, and the presence of a thick intra-caldera fill makes uncertain the extrapolation to depth of surficial volcanotectonic and morphotectonic elements such as observed faults, alignments of eruptive centres and thermal springs, drainage anomalies, etc. In these cases, together with subsurface geology data and analogue modeling, the study of deposit types and their distribution within related eruptive successions may provide an additional tool to recognise phases and styles of caldera collapses.

Here we describe the case of the Onano eruption, which is thought to have played an important role in the development of Latera Caldera (Vulsini Volcanic District, central Italy). We report a reconstruction of the event based on field analysis of deposits, studies of grain size, vesicularity of juvenile clasts and nature of lithic inclusions, along with re-interpretation of available subsurface geology data, aiming at assessing the relationships among eruption dynamics and the site, mechanism and timing of the corresponding stage of caldera formation. In particular, we consider the influence of collapse on changes of eruptive regime which we infer to have occurred during a single eruptive event.

Geologic background

The Vulsini Volcanic District is located at the northwestern end of the Quaternary Roman Comagmatic Region (central Italy). Volcanism in the Vulsini area spanned 0.6–0.1 Ma and occurred at five major volcanic complexes and several tens of minor eruptive centres (Vezzoli et al. 1987; Fig. 1). Compositionally, the Vulsini eruption products encompass the entire spectrum of potassic rock types, with a predominance of trachytes and phonolites in terms of erupted volumes. The Latera Volcanic Complex developed in the western part of the district between 0.3–0.1 Ma. Its activity was dominated by Plinian and pyroclastic flow-forming explosive eruptions and gave birth to a stratovolcano truncated by a polygenetic collapse caldera in its central area. The final activity from intra- and circum-caldera centres was characterised by strombolian, hydromagmatic and effusive styles. For a detailed reconstruction of the stratigraphy of the Latera Volcanic Complex the reader is referred to Sparks (1975), Vezzoli et al. (1987), Palladino and Valentine (1995) and Palladino and Agosta (1997).

Present-day Latera Caldera has a broadly elliptical shape, elongated NNE-SSW, with axes of 9 and 7 km. The northern and eastern morphological rims are still well preserved and rise more than 200 m above the caldera floor, located at about 400 m a.s.l.. In particular, the eastern rim cuts the wide volcano-tectonic depression which is partially filled by Lake Bolsena. A minor depression located in the northwestern sector of Latera Caldera, which hosts Lake Mezzano, is also interpreted as a small caldera, called Vepe Caldera. Several eruptive centres, mostly consisting of scoria cones and associated lava flows, dot the caldera floor and nearby extra-caldera areas.

The origin and structural evolution of Latera Caldera was discussed by Nappi (1969), Sparks (1975) and Metzeltin and Vezzoli (1983). Gravimetric, geoelectrical and deep drilling data from geothermal exploration carried out in the caldera area by ENEL-AGIP joint-venture provided valuable information on subsurface geology which, along with petrographic and geochronological data on buried rock types, allowed a reconstruction of caldera collapse geometries and timing (Barberi et al. 1984). Evidence of incremental growth in the Latera Caldera was presented by Nappi et al. (1991). The apparent simplicity of the topographic caldera masks the fact that it is actually a complex caldera system with at least three nested depocentres. In this regard, the study of collapse-related eruptions may provide a contribution to the reconstruction of main phases of caldera evolution.

The Onano eruption succession

The Onano eruption marks the final phase of the volumetrically most important period of Latera volcanic activity that was characterised by the emplacement of a series of widespread pyroclastic flows around the present caldera. Although age determinations for the Onano eruption are not available, the event can be reasonably placed at approximately 0.17 Ma on the basis of the existing geochronological dates of bracketing deposits (see Trigila 1985 and Innocenti and Trigila 1987 for a comprehensive review). The Onano eruptive products include a spatter-rich deposit called *Vulcanite complessa di Onano* (i.e., complex volcanic deposit) for its enigmatic nature by Nappi (1969) and associated *ignimbrite F* of Sparks (1975). Trigila and Walker (1986) discussed the emplacement of the *Onano spatter flow* claiming a new pyroclastic flow depositional mechanism. Marsella et al. (1987) provided a detailed study of depositional and compositional features of the *Onano Pyroclastic Formation*. According to their stratigraphic reconstruction, the Onano eruption succession comprises two coarse lithic-rich breccia units, two pyroclastic surge units and *spatter* flow deposits associated with “normal ignimbrite” units. Previous studies recognised the Onano eruption as related to a late stage of caldera collapse. In particular, G.P.L. Walker (unpublished study) identified the Onano eruption succession as typical of a caldera-forming eruption related to the occurrence of an excellent example of co-ignimbrite lag breccia.

The Onano eruption products overlie a consolidated yellow ash flow deposit with disperse black scoria lapilli, the main unit of the *Grotte di Castro* eruption (*Grotte di Castro Formation* of Vezzoli et al. 1987), which broadly corresponds to Ignimbrite E of Sparks (1975). A clear stratigraphic discontinuity is generally lacking, so only a short period of time may have elapsed between the two eruptions. Locally, intervening minor pyroclastic deposits with an immature paleosol on top provide evidence of a relatively brief temporal hiatus between the two eruptions. An immature paleosol developed on the final products of the Onano eruption (see *hydromagmatic and strombolian deposits* below) underlies hydromagmatic and strombolian deposits of the *Poggio Pinzo* pyroclastic

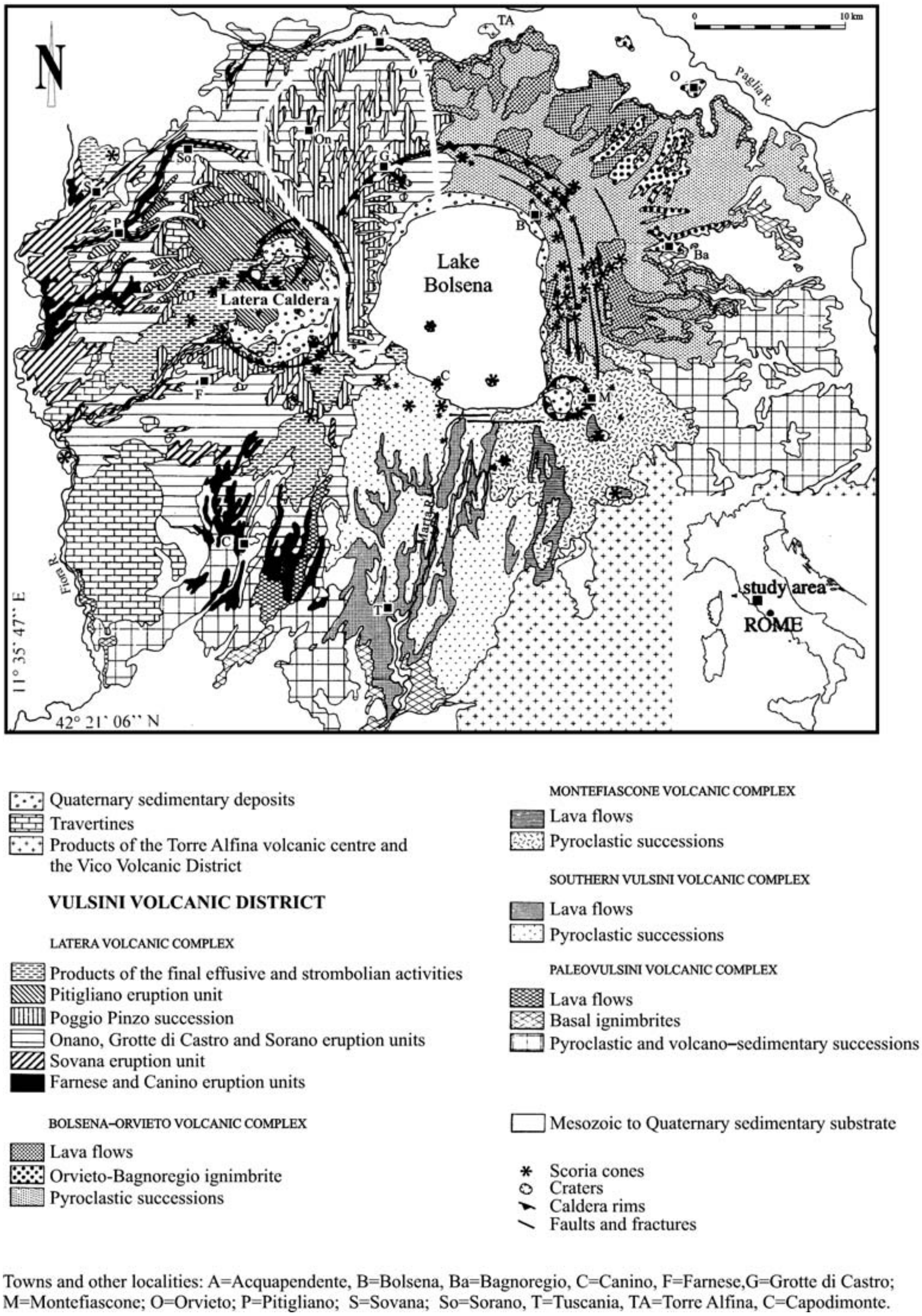


Fig. 1 Geological sketch map of the Vulsini Volcanic District (after Vezzoli et al. 1987, modified). The *white line* encloses the outcrop area of the Onano eruption products (see Fig. 2)

succession (*Tufi di Poggio Pinzo member* of Vezzoli et al. 1987; Palladino and Taddeucci 2000), which are widely distributed around the present caldera. The Onano eruption products crop out extensively northeast of the present Latera Caldera rim, as far as Acquapendente (13 km away), and along radial valleys cutting the eastern Latera volcano slopes up to the Bolsena lakeshore (Fig. 2). Moreover, limited exposures of intracaldera facies occur along the present-day eastern wall of Latera Caldera. From the observed areal distribution and thickness, the estimated volume of erupted products is on the order of 1 km^3. From field evidence and remote sensing imagery, different authors have suggested a fissure-like vent bordering Latera Caldera to the east (Nappi 1969; Marsella et al. 1987; Freda et al. 1990) for this eruption.

The eruption stratigraphy reconstructed in the present study re-examines previous work (Trigila and Walker 1986; Marsella et al. 1987) and includes new field investigations (Fig. 3). The depositional units identified are described below in stratigraphic order. Generally their

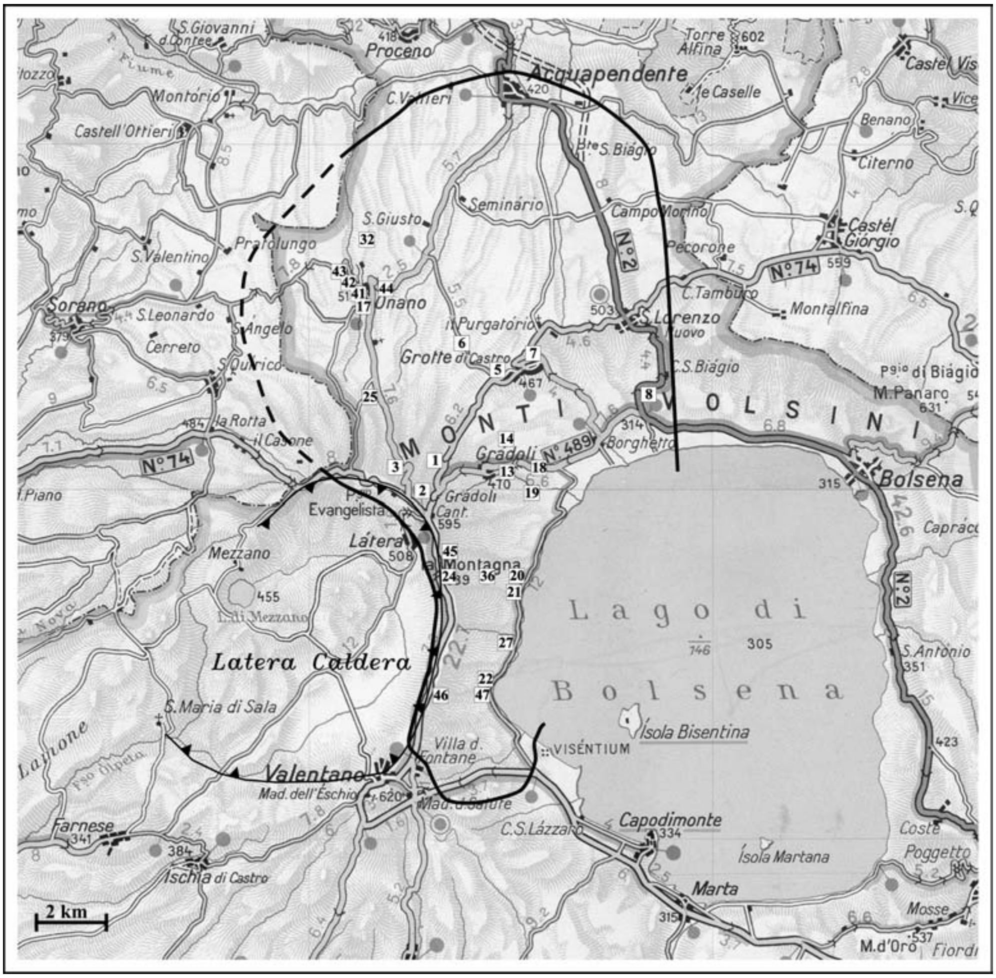


Fig. 2 Limits of outcrop area of the Onano eruption products (*solid line*). The *dashed line* indicates some uncertainty in the Onano-Sorano area. Numbered outcrop localities are cited in the text as "*O*" followed by corresponding numbers. The locations of the stratigraphic logs of Fig. 3 are also reported

transitions are gradual and marked by changes of component proportions (i.e., pumice, *spatter*, lithic) and grain size and/or degree of vapour-phase consolidation, consistent with an origin from a single eruptive event.

In our description below, the term *sillar* refers to a non-welded pyroclastic flow deposit indurated during vapour-phase crystallisation that formed zeolite minerals, e.g., chabazite and phillipsite; the term *spatter* is used for semi-molten scoria clasts that readily agglutinate upon deposition (Fisher and Schmincke 1984; Trigila and Walker 1986).

Stratigraphy

Lower sillar

The basal unit of the Onano eruption succession comprises well stratified and massive ash flow deposits containing pumice and spatter clasts, respectively. The transition from stratified to massive facies normally occurs upsection and is marked by an abrupt increase of spatter and lithic vs. pumice clast content. Commonly this unit directly overlies the *Grotte di Castro* eruption products, while it locally rests on top of an immature paleosol that divides the Onano eruption products from partially reworked, minor pyroclastic surge and lithic-rich scoria fall deposits (>2 m thick at localities O46, O47; numbered localities are shown in Fig. 2) and *Grotte di Castro* eruption products underneath. Generally, a gradual upward transition to the *lower spatter* (see below) is observed.

The well stratified facies is exposed in the area between the eastern rim of Latera Caldera and Lake Bolsena (e.g., O46, O47; Fig. 3), where it locally exceeds 6 m in thickness. It is made up of light grey, moderately vesicular juvenile lapilli, sparse lithic lapilli and isolated spatter blocks set in a mainly unconsolidated ash matrix. Diffuse decimetre-spaced trails of pumice lapilli define plane-parallel and subordinate low-angle cross-stratification, which are interpreted as traction sedimentation features developed at the base of turbulent pyroclastic currents. Interbedded thin fine ash layers indicate that settling of fine material occurred among different flow events. Minor lithic-rich scoria fall horizons are also present. In some exposures the stratified facies directly underlies the *lower spatter* and shows vapour-phase consolidation (O13, O27). In more proximal exposures (e.g., O24), lithic lapilli and decimetre-sized blocks are

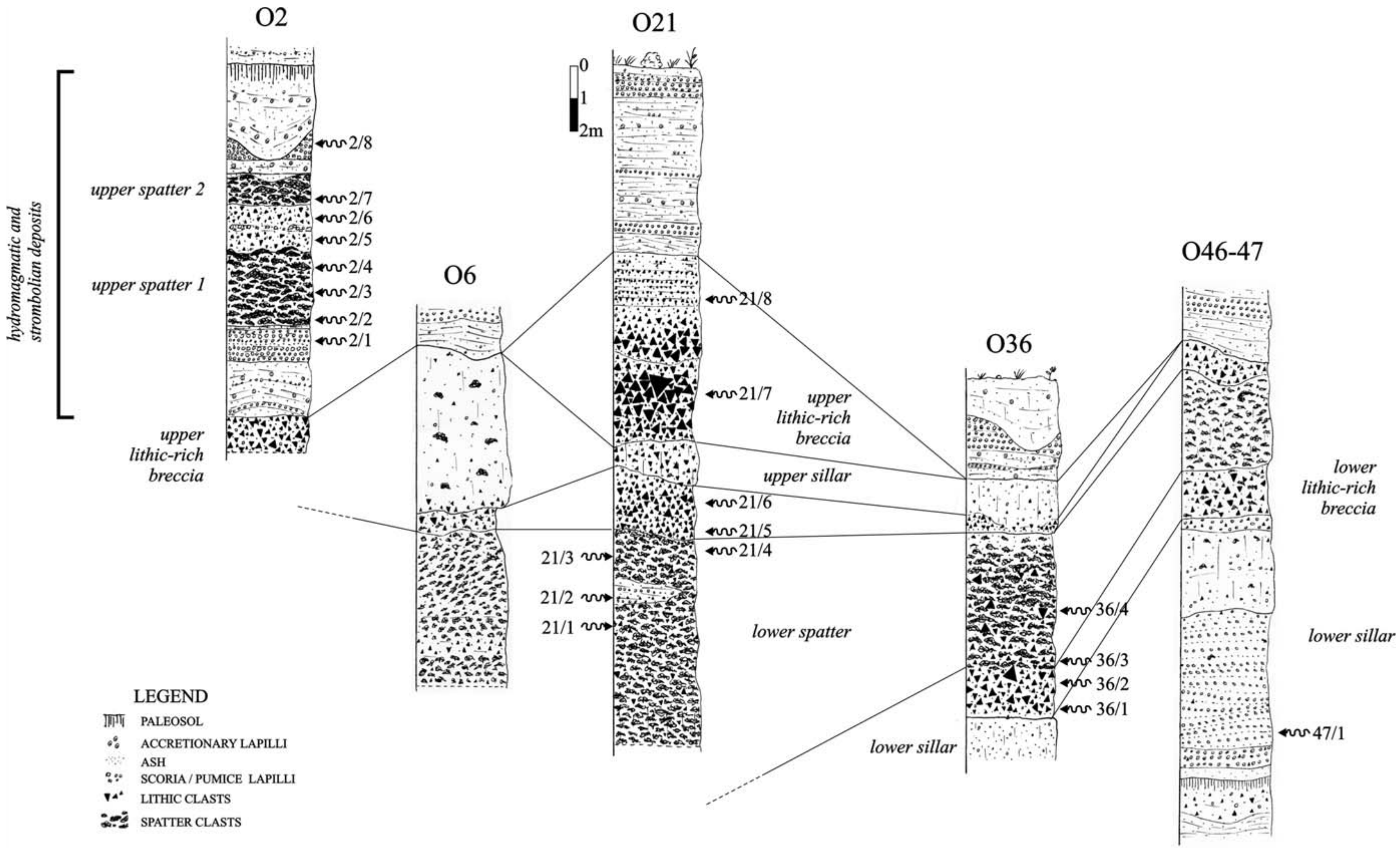


Fig. 3 Representative stratigraphic logs of the Onano eruptive succession (log labels refer to numbered localities reported in Fig. 2). The locations of samples for grain size, component and juvenile clast density analyses are also shown

Table 1 Component data for the Onano lithic-rich breccia deposits in the −2 to −3 Φ (4 to 8 mm) grain size class. Component abundances were determined after hand-picking and are expressed as weight percentages. Sample labels are as in Fig. 3

Unit	Sample	Juvenile light pumice	Juvenile dark scoria	Free crystals (clinopyroxene)	Cognate lithic (lava and subordinate pyroclastic)	Accidental lithic (carbonate)	Accidental lithic (other sedimentary)
Upper lithic-rich breccia	21/8	48.2	4.9	-	28.5	5.8	12.6
	21/7	25.7	5.1	-	50.4	6.8	12.0
	21/6	0.5	54.3	-	36.2	-	9.0
	21/5	-	36.3	0.2	56.7	-	6.8
Lower lithic-rich breccia	36/2	-	68.4	0.2	27.7	-	3.7
	36/1	-	64.3	-	31.7	-	4.0

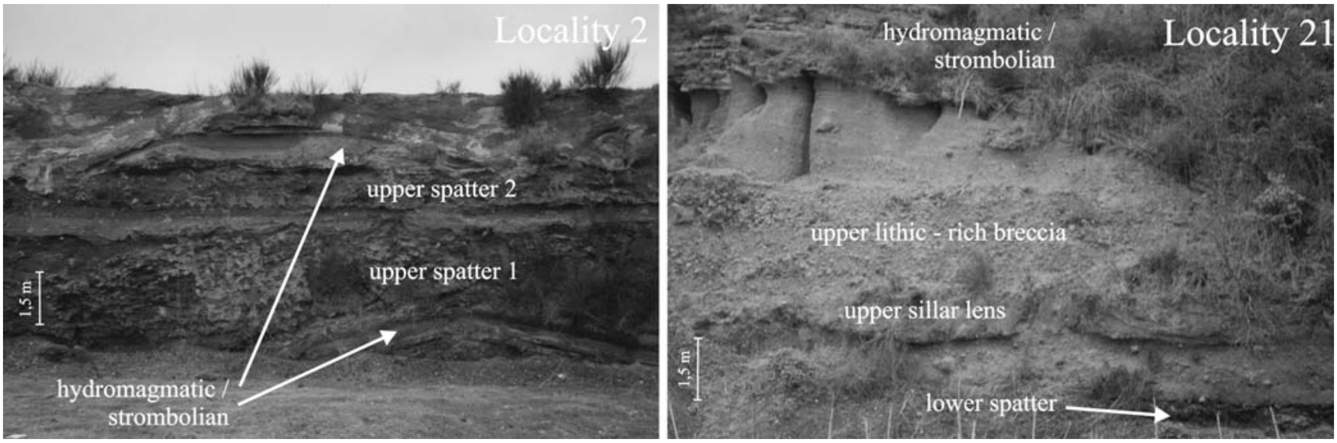


Fig. 4(a, b) (a) Locality 2: upper part of the Onano eruptive succession. The *upper spatter 1* shows an undulating lower contact and a nearly horizontal upper contact, consistent with its inferred flow origin. Meter-spaced waves characterise the top surfaces of both spatter units. Also note strombolian fall deposits that mantle—and pyroclastic surge deposits that fill—erosional channels in the upper part of the outcrop. **(b)** Locality 21: the *upper lithic-rich breccia* overlying the *lower spatter* is coarser-grained and massive in the lower-middle part, with an interlayered sillar lens, and finer-grained and stratified upward. Note the upper erosional contact with co-eruptive and Poggio Pinzo hydromagmatic and strombolian deposits

quite abundant and are arranged in layers, swarms or lenses, with overall inverse grading.

The upper massive facies is the most widely distributed, being recognised as far as Acquapendente, and consists of an indurated yellowish ash deposit, up to 4 m thick (sillar; *tgr'* unit of Marsella et al. 1987), which contains sparse black scoria lapilli and blocks. The massive appearance, poor sorting and matrix support, along with post-depositional vapour-phase induration implying entrapment of juvenile gas, indicate a pyroclastic flow origin.

Lower lithic-rich breccia

In places (e.g., at localities O36, O46), lithic lapilli and blocks up to 1 m in size are concentrated on top of the *lower sillar* to form a slightly indurated breccia with a fines-poor matrix of millimetre-sized, moderately vesicular grey-reddish scoria fragments (see Table 1 for component abundances). This unit is 1–1.5 m thick and gradually passes upward to a lithic-rich spatter agglomerate (*lower spatter*).

Lower spatter

The most distinctive deposit of the Onano eruption (Fig. 4) is a several metres-thick, massive to crudely stratified agglomerate of brick-red, purple or black spatter lumps, with a coarse ash matrix. Centimetre- to metre-sized spatter clasts are moderately to strongly flattened with lensoid to contorted ribbon-like shapes. Typically, their long axes are broadly parallel to the depositional surface or define an imbricated fabric. Centimetre- to decimetre-sized lithic clasts are also abundant. In places, a stratified appearance is caused by multiple, massive to inversely graded, spatter-rich and lithic-rich horizons or lenses (O6, O14). This deposit varies from unconsolidated, with only incipient agglutination of coarse spatter, to strongly welded, which resembles a dense aphanitic lava flow. The upward transition from non-welded to welded facies may occur in single outcrops (e.g., O13, O22). Locally there are finer-grained, coarse-ash-matrix-supported portions with variable degree of induration (O5).

This unit passes downward (and in some cases also laterally) into the massive facies of the *lower sillar*. At proximal localities (e.g., O24), it shows an undulating, sharp lower contact with metre-sized channels carved into the oxidised ashy top of the *lower sillar*. Generally, the gradational upward transition into the *upper sillar* is marked by an abrupt increase of ash matrix and degree of consolidation, or locally by interbedded lithic-rich lenses or discontinuous layers (e.g., O14, O17). Degassing pipes are observed to cross from the *lower spatter* into the *upper sillar* for several decimetres (e.g., O14), indicating that no significant time occurred between the emplacement of the two units. A gradational contact from lithic-rich spatter deposits, through spatter-rich lithic breccia, to pumice-rich lithic breccia (*upper lithic-rich breccia*) is observed at proximal locations (e.g., O3, O21).

The *lower spatter* crops out extensively to the east and northeast of Latera Caldera as far as Onano and Acquapendente and the Bolsena lakeshore (Fig. 2). Deposit thickness, besides its general decrease away from the inferred vent, varies considerably in response to pre-existing topography and tends to increase in depressions to a maximum of 16 m (e.g., Gradoli area). On a regional scale, the size of spatter and lithic clasts does not vary systematically with distance from the vent, whereas it appears to be crudely related to deposit thickness and controlled by topography. The overbank facies are characterised by reduced thickness (to about 1 m) and grain size, with sparse spatter coarse lapilli and blocks set in a black coarse ash matrix (e.g., O42, O43).

Apart from the local occurrence (e.g., O14, O21) of decimetre-thick scoria lapilli horizons, which are rich in spindle-shaped breadcrusted bombs and exhibit clear evidence of emplacement by fallout (i.e., good sorting, mantle bedding, etc.), textural features suggest that the *lower spatter* deposits generally were emplaced by lateral flow transport rather than by fallout. These include lack of impact sags, occurrence of imbricated clasts, ash matrix, coarse-tail grading, lithic-rich lenses or discontinuous lithic trails, and deformation of spatter in a down-flow direction in response to local obstacles such as large lithic blocks (cf. Mellors and Sparks 1991). Although some of the above features can be ambiguous, as they can also occur in more or less remobilised, partially welded pyroclastic fall deposits from hawaiian-strombolian activity, the irregular maximum clast size distribution on regional scale and strong topographic control on deposit thickness provide strong arguments for an emplacement by flow. Another line of evidence is that in individual stratigraphic divisions the degree of flattening and deformation (including rolling) of hot, plastic spatter clasts, as well as their imbrication, increases toward the top and thus can not be related to loading effects on spatter material after deposition. More likely this feature resulted during transport in a sheared pyroclastic current and/or by shear exerted by overriding material flowing on just-deposited spatter during incremental deposition (Trigila and Walker 1986; Branney and Kokelaar 1992). In particular, Branney and Kokelaar (1992; see their Fig. 5) report the imbrication pattern of the Onano spatter as a good example of syn-agglutination imbrication during progressive aggradation of a pyroclastic current.

On the other hand, rheomorphism cannot explain the observed texture of the spatter deposits, since they retain their typical appearance in most exposures where they rest on nearly flat or slightly inclined surfaces. Similar spatter-rich deposits that have been interpreted as having been emplaced by pyroclastic currents are described in caldera environments (e.g., Pantelleria, Orsi and Sheridan 1984; Santorini, Mellors and Sparks 1991; Phlegraean Fields, Perrotta and Scarpati 1994) or associated with relatively small mafic composite cones (Valentine et al. 2000).

Upper lithic-rich breccia

This deposit was first recognised by G.P.L. Walker (unpublished study) as one of the best examples of co-ignimbrite lag breccia he had observed. Distinguishing criteria from proximal fall deposits (i.e., lack of impact sags, strong topographic control on thickness, close association with "normal" pyroclastic flows, etc.) mostly follow Walker (1985). The most complete exposure occurs at locality O21, where the unit is 6 m thick (Fig. 4). The lower-middle part is a chaotic agglomerate of lapilli- to boulder-sized accidental and accessory lithic clasts up to 1 m and subordinate black spatter lapilli set in a fines-poor, coarse ash matrix rich of light grey, rounded pumice fragments (see Table 1 for component abundances). Clast-supported lenses are also common. This part of the deposit has an overall inverse to normal grading and is interpreted as having been emplaced by suspension sedimentation from an unsteady, turbulent pyroclastic current (see deposit type 1b and corresponding flow scenario, Palladino and Simei 2001). An interbedded reddish sillar lens, up to 1 m thick, is also present. The upper part lacks large blocks and has a stratified appearance because of multiple, laterally discontinuous, centimetre- to decimetre-thick, inversely graded divisions rich in lithic lapilli, which are interpreted as traction sedimentation layers (type 2, Palladino and Simei 2001).

Elsewhere the coarse lithic breccia is a few metres thick, massive to crudely stratified because of grain size changes, content and type of lithic components. Locally, imbrication of lithic lapilli and gas-escape structures provide further evidence of deposition from a primary pyroclastic current. In some exposures (e.g., O3), matrix material below large lithic blocks is coarser-grained (i.e., lapilli-sized) and notably fines-poor, which likely indicates that the displacement of heavy blocks in the transporting flow caused the upward flux of interstitial juvenile gas and fines (hindered settling mechanism, Druitt 1995) and/or some fluidisation effect.

In proximal areas extending from the present caldera rim to Lake Bolsena, the lithic breccia either replaces or grades both upward and laterally into the *upper sillar*. In the last case, the transition is defined by an abrupt decrease of lithic content and increase of the ash proportion and degree of vapour-phase consolidation. Degassing pipes are observed to cut the unit boundary and the lithic-rich base of the sillar (e.g., O1). In some exposures, the breccia appears as discontinuous, decimetre- to metre-thick, lithic-rich layers or lenses, which are either intimately interstratified with the *upper sillar* (O14, O18, O17), or channelled into underlying deposits (O36, O20, O44). In places (i.e., O19), two distinct breccia units are separated by a 0.5 m thick coarse ash bed rich in accretionary lapilli.

Upper sillar

Typically this is a few metres thick deposit made of black scoria clasts set in a yellow-reddish ash matrix, indurated during vapour-phase crystallisation. This unit broadly corresponds to *ignimbrite F* of Sparks (1975) and *tgr* unit of Marsella et al. (1987) and shows clear evidence of an origin from a pyroclastic current. Because it is rarely found in proximal settings due to discontinuous portions interfingering with the *upper lithic-rich breccia*, it can be considered as the downcurrent equivalent of the coarse breccia facies. The *upper sillar* is the most widespread unit of the Onano eruption; it crops out mostly to the north and northeast of Latera Caldera as far as Acquapendente, with a maximum observed thickness of more than 5 m between Grotte di Castro and Onano (O6). Northwest of Latera Caldera where co-eruptive spatter deposits were not emplaced, the *upper* and *lower sillar* units may merge so that are not easily distinguished from each other and from minor pyroclastic flow units with similar field appearance and analogous stratigraphic position (i.e., S. Quirico-Sorano area; Fig. 2).

Usually the basal contact with the *lower spatter* is gradational and cut by degassing pipes. However, in a few cases (e.g., O41), the *upper sillar* fills metre-wide channels carved into the *lower spatter*, suggesting at least a brief time between the two flow events. In other cases (e.g., O36) the boundary between the two units is shown by a decimetre-thick, fine-grained basal layer above which lithic clasts are concentrated.

Normally, centimetre-sized lithic clasts are abundant toward the base, but isolated blocks up to several decimetres in size can be also present. The deposit is generally massive, although flattened black spatter clasts can be iso-oriented or locally organised in steeply inclined or imbricated clusters. Decimetre- to several metres-sized, clast-supported, fines-poor, lenses of black spatter blocks and lithic lapilli also are enclosed (O7, O32), which resemble the *lower spatter* deposits underneath. Diffuse decimetre-wide degassing pipes and pockets mostly originate from these spatter-rich lenses.

In some cases, abrupt changes in matrix grain size mark lateral transitions from indurated to non-consolidated portions (e.g., O7, O25). For example, indurated portions are rich in fine ash, whereas non-consolidated portions show a fines-poor matrix of well rounded, dark grey, millimetre-sized pumice grains, abundant leucite crystals and accretionary lapilli, either sparse or concentrated in pockets. Locally (e.g., O25), a few metres thick, channelled sillar facies with associated basal lithic-rich lenses grades laterally on an outcrop scale to an overbank facies consisting of a decimetre-thick, non-consolidated deposit of coarse ash and fine pumice lapilli which is rich in accretionary lapilli.

In places (e.g., O25, O7, O8), several decimetre-thick ash horizons (overall thickness up to 1 m at O25), containing millimetre-sized lithic, pumice and accretionary lapilli either sparsely or in swarms, rest on top of the unit. Abundant degassing pipes originating from the sillar top are observed to cross all these layers, suggesting almost continuous deposition of co-ignimbrite ash fall and ash cloud surge deposits.

Hydromagmatic and strombolian deposits

These deposits include alternating, decimetre- to metre-thick, massive and planar to cross-stratified, pyroclastic surge deposits and massive to stratified strombolian scoria fall deposits that overlie the *upper lithic-rich breccia* or, where the latter is lacking, the *upper sillar*. Generally, a nearly horizontal stratigraphic contact is observed, although an erosional contact with evident angular unconformity locally cuts the stratified breccia (locality O21, Fig. 4). Total thickness decreases with distance from the present northeastern caldera rim from at least 6 m (e.g., O2) to less than 1 m south of S. Lorenzo Nuovo (O8).

Pyroclastic surge divisions are ash- to lapilli-sized, grey to greenish in colour and rich in accretionary lapilli. The presence of vesicular tuff layers, along with SEM grain textures (i.e., dominance of blocky, poorly vesicular ash particles with hydration cracks; Palladino and Taddeucci 2000), indicates an origin as wet pyroclastic surges of hydromagmatic origin. In the area of Cantoniera di Latera-Poggio Pinzo (O2, O3), scoria lapilli divisions from strombolian fallout enclose decimetre-sized lithic blocks with impact sags indicating a near vent location. In the same area, interbedded spatter deposits (see *upper spatter* below) are separated by discontinuous, mildly consolidated breccia horizons with an overall thickness up to 1.5 m, which contain abundant lithic lapilli and blocks set in a grey-brownish coarse ash matrix or locally arranged in clast-supported zones, variably vesicular black spatter lapilli, and a distinctive grey pumice-rich layer. The high lithic content and the broad range of juvenile clast vesicularity (see below) are consistent with a hydromagmatic eruptive interval. The gradational transitions to bracketing spatter divisions and, more generally, the multiple transitions from strombolian to surge activity that characterise the unit, may indicate that the eruptive style changed repeatedly from magmatic to hydromagmatic and vice-versa without significant time breaks. Alternatively, multiple vents may have been active simultaneously with contrasting eruptive styles.

Erosional channels a few metres deep are draped by scoria fall beds and filled with massive ash surge deposits and characterise the upper part of the unit (Fig. 4). The presence of an immature paleosol on top marks the end of the Onano eruption succession. Alternating strombolian and hydromagmatic activity styles are also typical of the overlying *Poggio Pinzo* pyroclastic succession (Palladino and Taddeucci 2000; *Tufi di Poggio Pinzo member* of Vezzoli et al. 1987).

Upper spatter

These deposits comprise one or two subunits consisting of metre-thick, loose to incipiently welded, clast-supported agglomerates of black spatter lapilli and blocks sometimes exceeding 1 m in size. Typically, individual spatter clasts are highly vesicular and easily crushable and have elongate or contorted shapes. Centimetre- to a few decimetre-sized lithic clasts are abundant and mostly are concentrated downward.

The *upper spatter* deposits are distributed over a limited area close to the northeastern rim of Latera Caldera. A single spatter unit is exposed at locality 1, while quarry outcrops near Cantoniera di Latera and Poggio Pinzo (O2, O3) expose two spatter subunits (*upper spatter 1* and *upper spatter 2*) as thick as 2–3.5 and 1.5–2 m, respectively, which are interlayered with the above described *hydromagmatic and strombolian deposits* (Fig. 4). At locality O2, the two subunits are observed to merge laterally where the interbedded hydromagmatic breccia pinches out. On undulating depositional substrates, spatter deposits appear to fill rather than mantle depressions (Fig. 4), consistent with a flow origin. Their top surfaces are characterised by metre-spaced waves, which do not appear to be related to post-depositional loading effects, although it is not clear whether this is a primary or rheomorphic flow depositional feature.

Other related deposits

In the area of La Montagna (O45), along the watershed between Latera Caldera and Bolsena depression, a dark grey lava ridge and associated feeder dykes and a partially welded spatter cone are thought to belong to the Onano eruption products and to indicate a fissure-like vent bordering Latera Caldera. The stratigraphic context and chemical composition of the lava, which is quite similar to that of the *lower* and *upper spatter* units (Marsella et al. 1987; see below), support this interpretation.

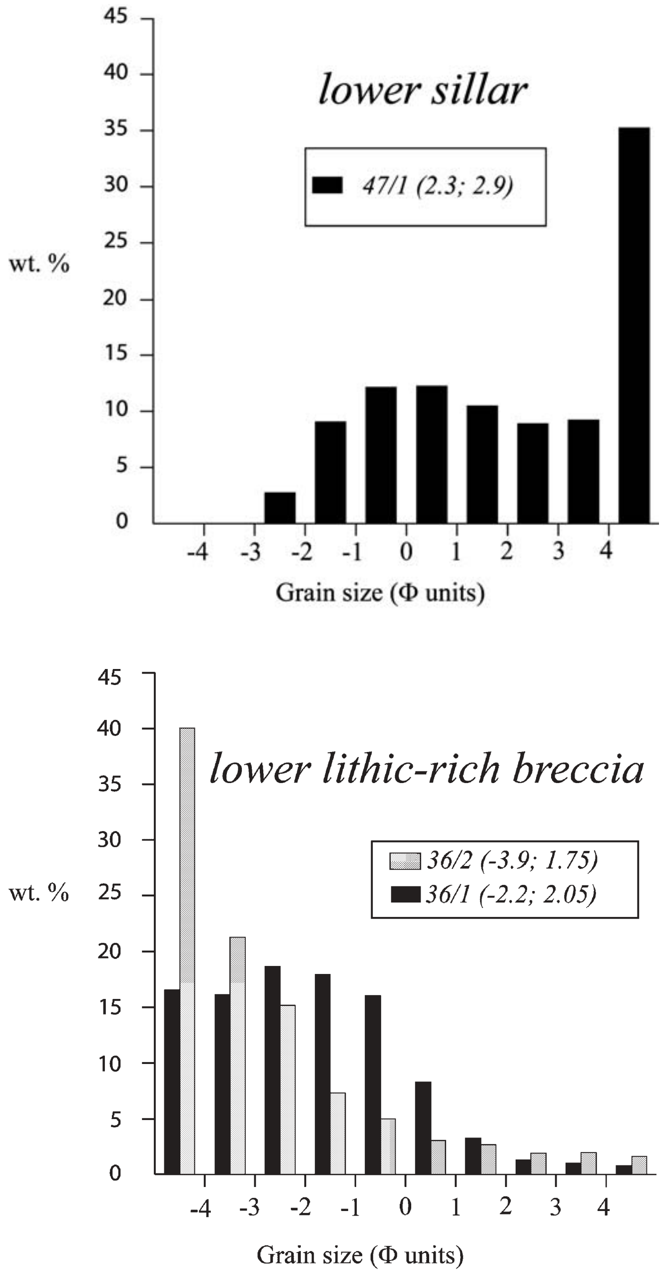
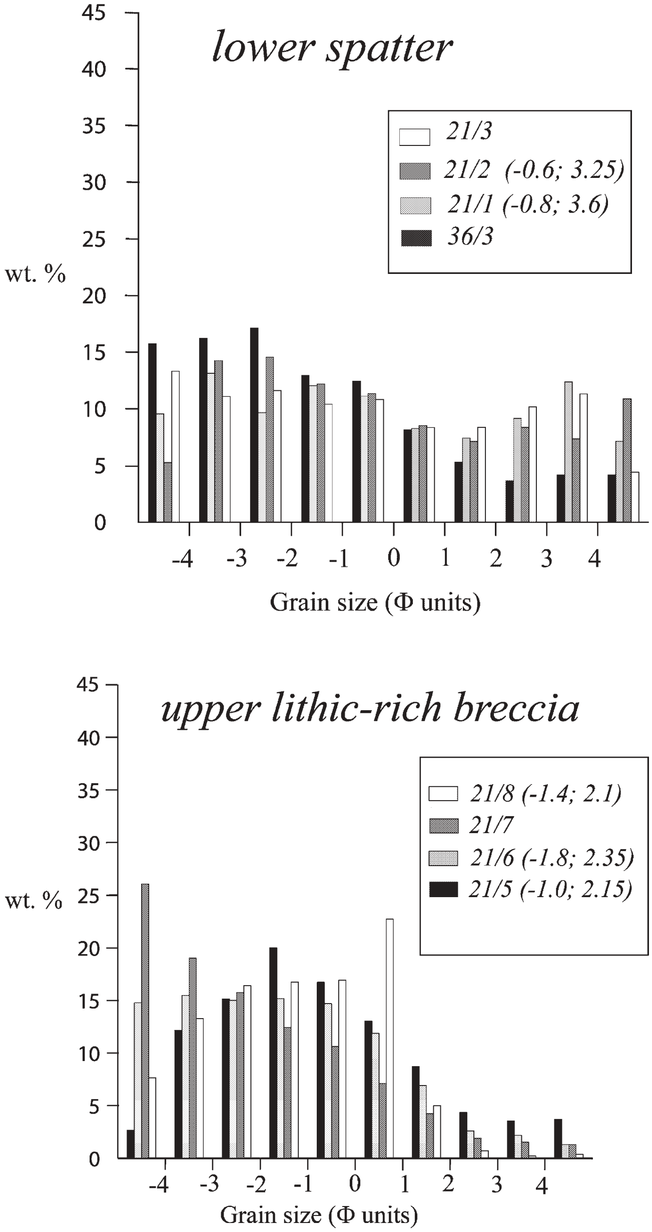


Fig. 5 Representative grain size analyses of the Onano eruption products. Sampled localities are reported in Fig. 3. All data are normalised to the fraction finer than 32 mm (-5 Φ). The fine ash contents of the *upper spatter* (i.e., samples 2/2, 2/3, 2/4, 2/7) are significantly overestimated due to considerable abrasion of spatter clasts during sieving. Numbers between brackets are the Inman parameters median (Md_{φ}) and sorting (σ_{φ}), respectively, calculated for the fourteen samples for which the whole grain size distributions were determined

Grain size features

Grain size analyses were carried out by dry sieving on nineteen samples from unconsolidated deposits. Sampled localities are reported in Figs. 2 and 3. Five samples from the coarsest-grained deposits were analysed in the fraction finer than 32 mm only, due to the low statistical significance of data on coarse lapilli and block fractions. Accordingly, for sake of comparison, the reported data set for all samples (Fig. 5) is normalised to the fraction finer than 32 mm. Grain size data of *upper spatter* deposits (four samples) were significantly affected by clast crushing during sieving and thus the reported fine ash contents are overestimated.

Grain size variations through the Onano eruption succession are related to the degree of magma fragmen-



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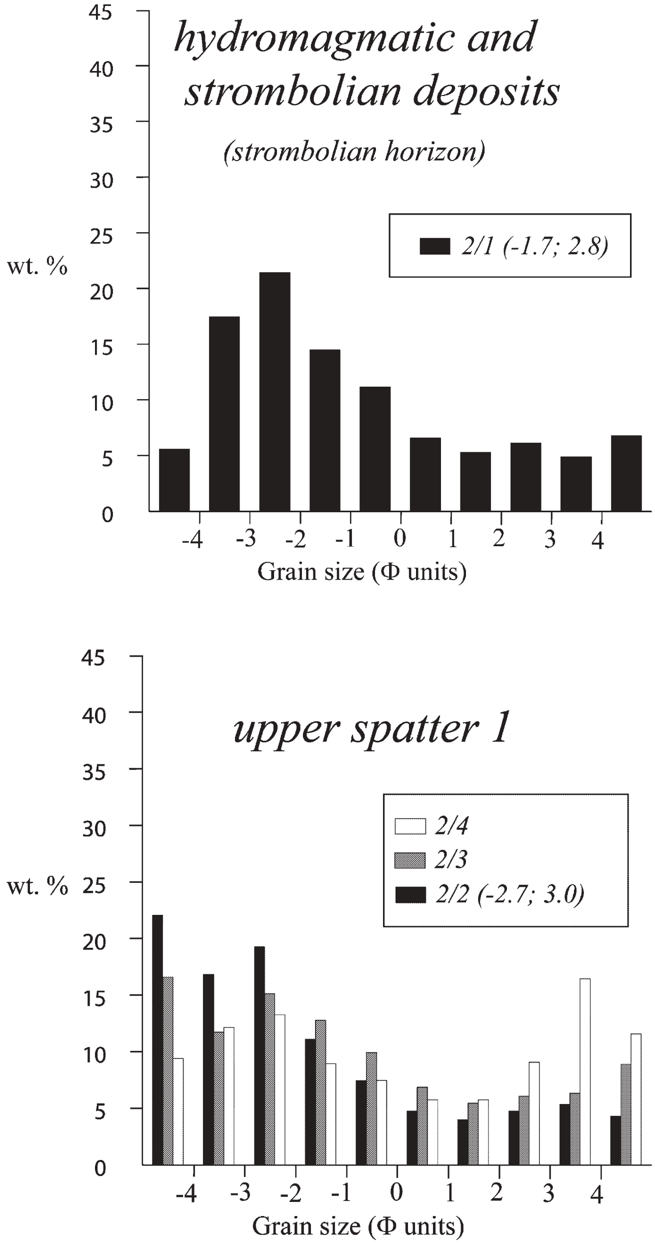

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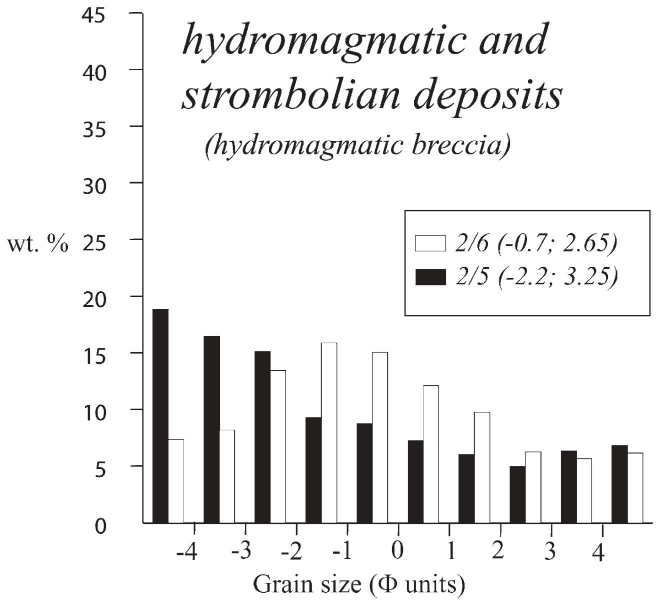
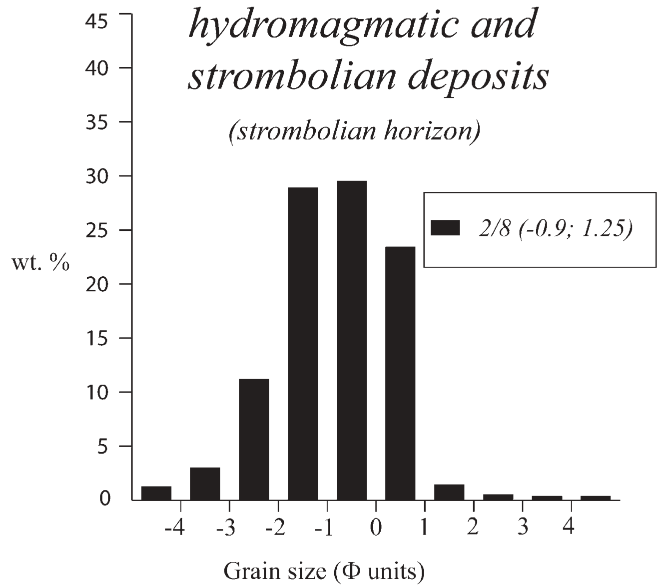
tation and emplacement mechanisms. The basal stratified facies of the *lower sillar* (i.e., sample 47/1 from a fine-grained division) is by far the most rich in fine ash (35% by weight for the grain size fraction <63 μm) among the Onano deposits. Bimodality and poor sorting (σ_φ=2.9) are consistent with its inferred flow origin. Conversely, the *lower lithic-rich breccia* is unimodal, moderately sorted (σ_φ=1.75–2.05) and remarkably fines-poor, the amount of fine ash being as low as 0.8–1.6 wt% in the analysed fraction. The *upper lithic-rich breccia* is also unimodal, moderately sorted (σ_φ=2.1–2.35) and fines-poor (0.4–1.3 wt% of fine ash), except at its base (3.7%). These features are typical of deposits described in the literature as "lag breccias" and consistent with an origin by direct suspension sedimentation of coarse material from turbulent pyroclastic currents. On the other hand, the *lower spatter* is polymodal and poorly sorted (σ_φ=3.25–3.6), with significant fine ash content up to 10.9 wt%, consistent with its inferred flow origin. In comparison, the *upper spatter* is unimodal to polymodal and slightly better sorted (σ_φ=2.6–3.0) and possibly less rich in fines considering the overestimated fine ash contents. The lithic-rich breccia horizons of inferred hydromagmatic origin (i.e., samples 2/5, 2/6), interbedded with the *upper spatter*, have sorting values of 2.65–3.25 and significant fine ash contents (>6 wt%). In comparison, a typical strombolian scoria fall bed upsequence (e.g., sample 2/8) is clearly unimodal and well sorted (σ_φ=1.25), with negli-





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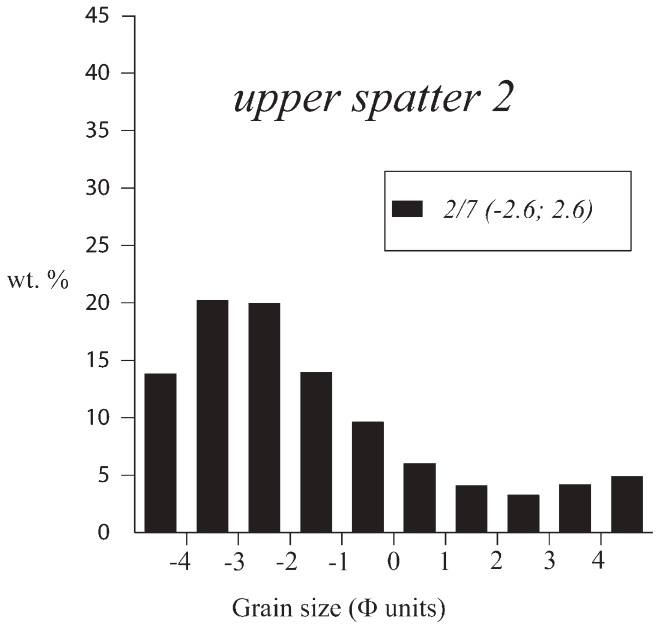


Fig. 5 (continued)

gible fine ash content. On the other hand, another sample from the topmost layer of a stratified strombolian fall deposit from the same unit (i.e., sample 2/1) is characterised by relatively high fine ash content (6.8%), possibly due to mixing with settling ash and/or post-depositional infiltration from an overlying thin ash surge layer.

Vesicularity of juvenile clasts

The degree of vesicularity of juvenile clasts was estimated by means of clast density measurements in the coarse lapilli (16–64 mm) and block (64–128 mm) size fractions, which are always a significant (often the most representative) component of the Onano deposits. Twenty-one samples covering the full eruption succession were taken at four proximal localities (Fig. 3). Clast density was determined by water displacement methods after coating individual clasts with impermeable films. For each sample, the average density of several (10–20) clasts was determined for the 16–32 mm size fraction, while the densities of individual clasts (5–11 clasts per sample) were determined for coarser size fractions (32–64 and 64–128 mm). Due to the low crystal content of juvenile clasts (2–7% by volume) and uniform chemical composition of the spatter (Marsella et al. 1987), density variations with stratigraphic height (Fig. 6) mirror changes in the degree of vesicularity. Given a dense rock equivalent (DRE) of about 2,600 kg/m^3 for the Onano spatter composition (see below), corresponding degrees of vesicularity range from <20 to 80% by volume. Despite some variability at each stratigraphic level, a vesicularity trend upsection is evident. The degree of vesicularity decreases upward in the *lower sillar* from pumice-rich, stratified to spatter-bearing, massive sillar facies, as evident from field observation. Relatively poorly vesicular spatter represents the dominant juvenile component of the *lower lithic-rich breccia* and *lower spatter* units. The occurrence of pumiceous clasts marks the transition to the *upper lithic-rich breccia*. Vesicularity then increases regularly through the *upper lithic-rich breccia* and reaches its maximum in the *upper spatter* (e.g., sample 2/2). Overall, vesicularity tends to decrease through *hydromagmatic and strombolian deposits*, with oscillations due to alternating spatter flow (i.e., sample 2/7), strombolian scoria fall (sample 2/8) and lithic-rich hydromagmatic horizons that show large variability and also contain poorly vesicular juvenile clasts (e.g., sample 2/5). Similarly, alternating strombolian beds with moderately vesicular scoria clasts and hydromagmatic beds with poorly vesicular juvenile clasts

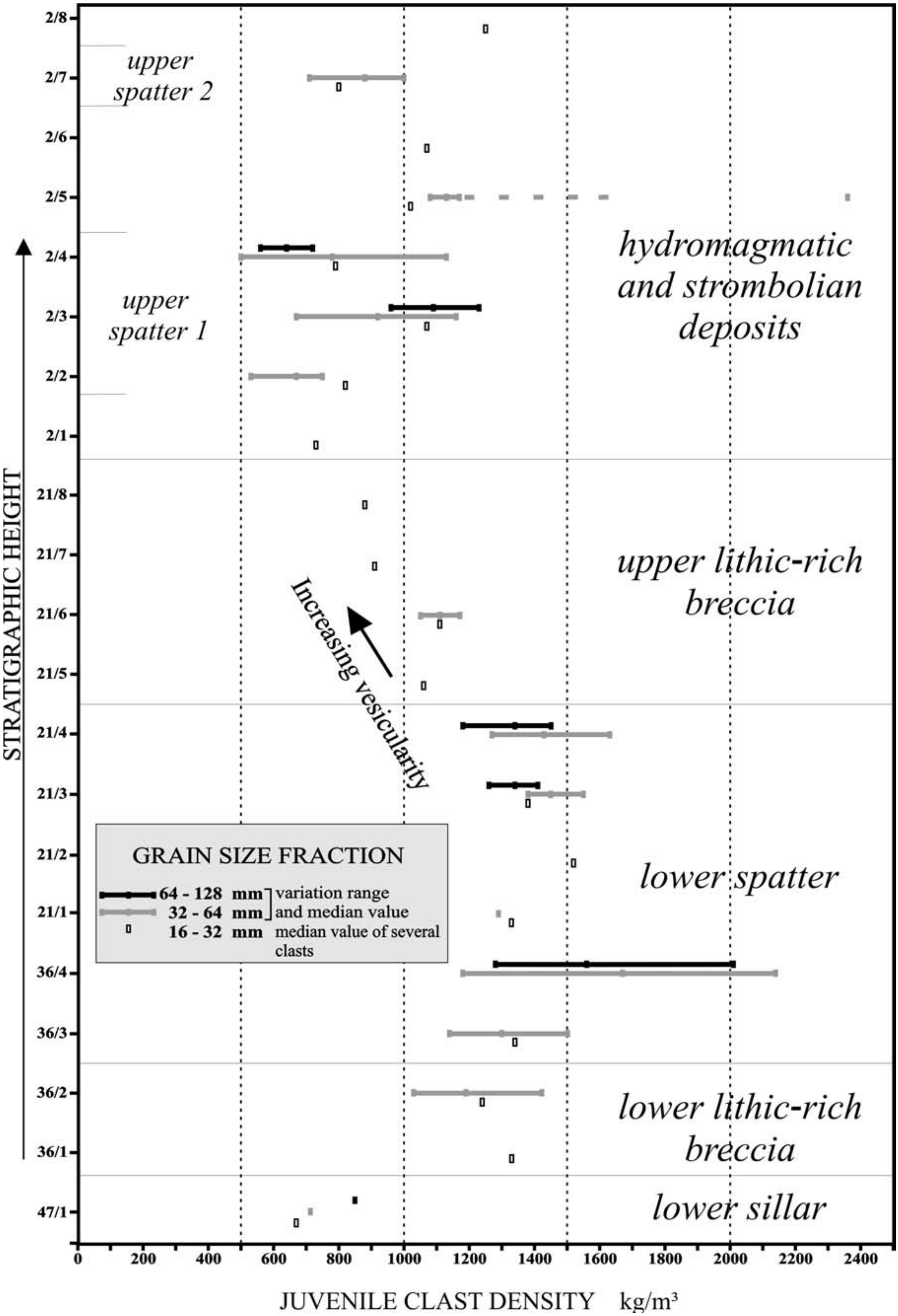


Fig. 6 Density variations of juvenile clasts through the Onano eruptive succession. The reported stratigraphic height is a composite stratigraphic log comprising four sampled localities (see Fig. 3). The clast density profile reveals temporal changes of the degree of magma vesiculation as a result of pressure changes in the magma chamber, as discussed in the text

have been found to characterise the succeeding *Poggio Pinzo* deposits (Palladino and Taddeucci 2000).

Compositional features of juvenile and lithic clasts

The composition of juvenile spatter clasts is homogeneous through the *lower* and *upper spatter* units and plots in the shoshonite and phonotephrite fields of the Total Alkali Silica diagram, with SiO_2 contents of 49–51 wt% and MgO 2–4 wt% (Barberi et al. 1984; Marsella et al. 1987). On the other hand, the *upper sillar* contains two compositionally distinct juvenile populations: i) black scoria lapilli and blocks with the same composition as in the spatter units and ii) light grey (or yellowish if altered), usually millimetre-sized pumice clasts which are trachytic in composition (SiO_2=62%, MgO~1%, on a volatile-free basis) (Marsella et al. 1987). The two types of juvenile components also characterise the matrix of the *upper lithic-rich breccia*, which shows a marked upward increase of light grey pumice vs. dark grey scoria content (see component analyses below, Table 1). It appears that two distinct magmas were involved in the Onano eruption: i) a batch of relatively mafic magma that also characterised the final post-caldera activity of the Latera Volcanic Complex and ii) a highly differentiated magma that may represent a residual portion of the magma reservoir which had fed the large explosive eruptions of older Latera activity (e.g., Vezzoli et al. 1987).

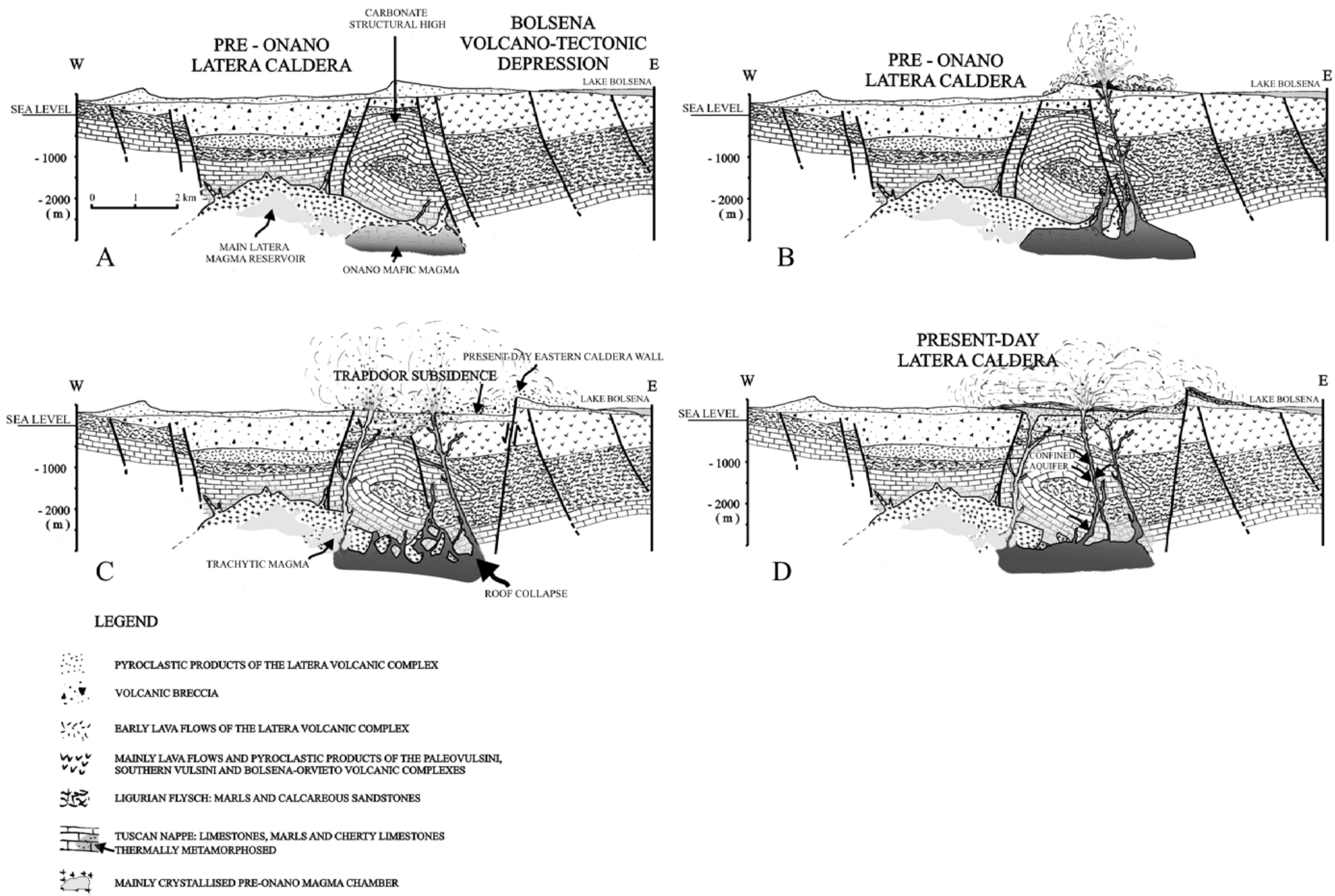
Lithic clasts in the *lower lithic-rich breccia* and *lower spatter* include different lava and pyroclastic rocks, hydrothermally altered clays, marls and calcareous sandstones of the Ligurian flysch, as well as holocrystalline syenite inclusions. The *upper lithic-rich breccia* marks the appearance of carbonate lithic lapilli and blocks of the Tuscan Nappe (limestones and cherty limestones), which also characterise the *upper spatter* and hydromagmatic divisions of the *hydromagmatic and strombolian* unit. The high variability of lithic content within individual units, both on regional and outcrop scale, as possibly due to strong topographic control on pyroclastic flow emplacement, as well as hydrothermal alteration that often masks lithic nature, prevents reliable quantitative estimates of lithic abundances in the field. Component data for the lithic-rich breccias were obtained for the $-2 \div -3\Phi$ grain size class (Table 1), which often approaches the modal size class of the analysed grain size fraction (see Fig. 5). Component analyses indicate that the lithic content reaches up to 36% by weight in the *lower lithic-rich breccia* and up to 69% in the *upper lithic-rich breccia* in the studied grain size class. Moreover, they show significant increase of accidental vs. cognate lithic ratio upsection and the appearance of carbonate fragments in the *upper lithic-rich breccia*. In addition, data from modal analyses in thin section (Marsella et al. 1987) show that the lithic content in the volumetrically most important unit of the Onano eruption, the *upper sillar*, ranges 2–21% by volume (~7% on average). In particular, igneous (i.e., volcanic and intrusive) fragments range 1–15 vol.% (~4% on average), whereas accidental (i.e., more or less thermometamorphosed and hydrothermally altered sedimentary) fragments attain abundances up to 8% (~3% on average). By taking into account the lithic-rich breccias and other units, the volume of the total lithic population extracted during the eruption is estimated at 0.1 km^3.

Observations of entrained lithic clasts from country rocks in the light of subsurface geology data (Barberi et al. 1984; Fig. 7) put constraints on magma withdrawal conditions during the different phases of the Onano eruption. It appears that magma ascent in the early eruption phases occurred through the peripheral eastern part of the older Latera Caldera where the substrate lacks carbonate rocks. During the climactic phase of the eruption leading to the emplacement of the *upper lithic-rich breccia*, magma ascent shifted toward the central part of the caldera and thus crossed carbonate rocks. Explosive interaction of magma with the confined carbonate aquifer characterised the late eruption phases.

Discussion: eruption dynamics and caldera collapse

The deposit characteristics and architecture described above strongly suggest that the Onano eruption dynamics were linked to a phase of caldera collapse. From the areal extent and depth of present Latera Caldera (9×7×0.2 km), the minimum volume of collapse is on the order of >12 km^3, which is much larger than the estimated volume of magma erupted during the Onano event (<1 km^3). Generally, the strong topographic control on pyroclastic flow distribution, loss of ash entering associated ash clouds and removal of products by erosion, as well as discontinuous exposure, prevent the production of reliable isopachs and calculation of total volume of deposits and corresponding magma erupted during Latera activity. However, by taking into account average thicknesses on the order of 1–10 m over areas of 10^3 km^2, individual volumes of deposits for the five major, pyroclastic-flow-forming Latera eruptions predating the Onano event (i.e., Canino, Farnese, Sovana, Sorano and Grotte di Castro) are on the order of 1–10 km^3, with a number of minor eruptions producing deposit volumes of an additional 0.1–1 km^3. Therefore, it appears that the present caldera volume is broadly consistent with the total magma withdrawn during the explosive activity of the Latera Volcanic Complex over a period of 0.12 Ma, indicating multi-stage caldera development. The Onano eruption was related to a late evolutionary stage, which brought Latera Caldera close to its present size, apart from the erosional retreat of the morphological rim. Subsequently, a minor collapse episode, probably related to the Pitigliano eruption (0.16 Ma), formed the small Vepe Caldera within Latera Caldera (Nappi et al. 1991).

Available information from field and subsurface geology provides clear evidence that a caldera existed before the Onano eruption. Deep drilling data from geothermal exploration revealed the presence of a structural high in the carbonate substrate elongated NNW-SSE in the central-eastern part of present-day Latera Caldera (Fig. 7), which was interpreted as the remnant of the


PRE - ONANO
LATERA CALDERA
CARBONATE
STRUCTURAL HIGH
BOLSENA
VOLCANO-TECTONIC
DEPRESSION
W
E
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SEA LEVEL
- 1000
- 2000
(m)
0
1
2 km
MAIN LATERA
MAGMA RESERVOIR
ONANO MAFIC MAGMA
A
PRE - ONANO
LATERA CALDERA
B
PRESENT-DAY EASTERN CALDERA WALL
TRAPDOOR SUBSIDENCE
TRACHYTIC MAGMA
ROOF COLLAPSE
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PRESENT-DAY
LATERA CALDERA
CONFINED
AQUIFER
D
LEGEND
PYROCLASTIC PRODUCTS OF THE LATERA VOLCANIC COMPLEX
VOLCANIC BRECCIA
EARLY LAVA FLOWS OF THE LATERA VOLCANIC COMPLEX
MAINLY LAVA FLOWS AND PYROCLASTIC PRODUCTS OF THE PALEOVULSINI, SOUTHERN VULSINI AND BOLSENA-ORVIETO VOLCANIC COMPLEXES
LIGURIAN FLYSCH: MARLS AND CALCAREOUS SANDSTONES
TUSCAN NAPPE: LIMESTONES, MARLS AND CHERTY LIMESTONES
THERMALLY METAMORPHOSED
MAINLY CRYSTALLISED PRE-ONANO MAGMA CHAMBER

eastern wall of an older and smaller caldera centred near present-day Lake Mezzano (Barberi et al. 1984). A rather uncertain K-Ar age of $\leq$0.9 Ma was reported for a syenitic intrusive body encountered at a depth of about 2 km below the present-day caldera floor, which was interpreted as the remains of a trachytic magma system related to the Vulsini "basal ignimbrites" and the early collapse phase (Barberi et al. 1984). According to Barberi et al.'s reconstruction, the eastern rim of the early Latera caldera was truncated by the western rim of Bolsena Caldera, which was subsequently intersected by the late Latera caldera following a new westward migration of the eruptive activity from Bolsena to Latera. This evolutionary model largely depends on the reported age value for the buried syenitic body. Although a reliable intrusion age is still lacking, it is likely that the syenitic body below the central Latera area is related to the magma chamber that fed the main period of explosive activity of the Latera Volcanic Complex (0.3–0.2 Ma) predating the Onano event rather than to the "basal ignimbrites" (0.6 Ma; Fig. 1) for which an eruptive source in the Latera area is unlikely. Consequently, we suggest that the formation of the early Latera caldera, as revealed by subsurface geological data, was linked to the trachytic to phonolitic explosive activity of the Latera Volcanic Complex and, in particular, to the period comprising the Canino and Sovana eruptions (0.28–0.19 Ma). The volume of magma erupted during this period can be estimated at >10 km^3, which is roughly the same order of magnitude as the collapsed volume of the early caldera as inferred from subsurface data (Barberi et al. 1984).

The early history of the Latera Volcanic Complex was characterised by recurrent Plinian activity leading to the emplacement of extensive pumice fall and flow deposits (Palladino and Valentine 1995, Palladino and Agosta 1997). The Sovana eruption, which can be linked to a major stage of caldera collapse due to the presence of a voluminous lithic-rich breccia facies, marked the onset of a new period of activity (approximately 0.19–0.17 Ma), during which eruption styles were essentially characterised by non-Plinian collapsing fountains mostly forming widespread ash flow deposits (i.e., Sorano, Grotte di Castro and minor eruptions). This may indicate that the disruption of the central conduit system due to caldera collapse led to explosive eruptions through multiple vents and ring fissures, the widened vent system and high mass discharge rates favouring collapsing vs. sustained Plinian columns. Although considerable volumes of magma (on the order of some km^3) were erupted during individual events that followed the Sovana eruption (i.e., Sorano and Grotte di Castro), the relative lack of lithic-rich breccias implies that extensive caldera collapses did not occur during post-Sovana, pre-Onano eruptions.

Therefore, it is likely that the roof of the partially evacuated magma chamber was structurally unstable and prone to collapse at the onset of the Onano eruption, so that this comparatively low-magnitude event could trigger an important phase of caldera development. Moreover, the Onano eruption took place in an area of structural weakness corresponding to a carbonate substrate high located between the eastern rim of the pre-existing Latera caldera and the western margin of the Bolsena volcano-tectonic depression. Intersecting rim fault systems favoured the ascent of mafic magma, represented by the shoshonitic to phonotephritic spatter, and its eruption in a decentralised area of the Latera volcano with a probable fissure style, as also suggested by previous authors (Nappi 1969; Marsella et al. 1987; Freda et al. 1990).

A reconstruction of the Onano event is illustrated in Fig. 7. The emplacement of ash- and pumice-rich pyroclastic currents (*lower sillar*) in the early phase of the eruption was followed by energetic fire-fountaining that produced lithic- and spatter-rich, moderately to strongly welded flow and subordinate fall deposits (*lower lithic-rich breccia* and *lower spatter*). The *lower sillar* and overlying *lower spatter* record a progressive decrease of magma vesiculation and fragmentation with declining magma pressure in the course of the eruptive phase leading to caldera collapse. The *lower lithic-rich breccia* may indicate incipient collapse. The partial evacuation of the magma chamber and concomitant decline of magma pressure induced destabilisation of the structurally weak and thermally altered roof of the magma chamber, eventually initiating caldera collapse. The significant increase of lithic content in the spatter deposits passing to the *upper lithic-rich breccia* indicates the availability of loose, collapse-derived debris in the feeding system. The lithic-rich breccia and the main pyroclastic flow (*upper sillar*) probably erupted through a widened fissure vent system and marked the eruption climax with maximum magma discharge rate.

The collapse involved the eastern part of the old caldera floor and nearby extra-caldera volcano slopes. As a

Fig. 7(A–D) Reconstruction of the Onano eruption and concomitant caldera collapse along a W-E section across Latera Caldera. Subsurface geology data after Barberi et al. (1984; modified). A) During the main period of explosive activity of the Latera Volcanic Complex (0.3–0.2 Ma) predating the Onano eruption, a polygenetic caldera formed to the west of Bolsena volcano-tectonic depression. B) Onset of the Onano eruption through fissures bordering the carbonate substrate high located between the former Latera caldera and Bolsena volcano-tectonic depression. The emplacement of ash and pumice flow deposits was followed by energetic fire-fountaining producing lithic- and spatter-rich flow (and subordinate fall) deposits. C) Magma withdrawal induced collapse of the structurally weak, thermally altered roof of the magma chamber. Trapdoor collapse involved the eastern part of the old caldera floor and external volcano slopes and cut the western margin of Bolsena volcano-tectonic depression. The main pyroclastic flow and associated lag breccia were erupted during the climactic phase of the eruption, the widened fissure system allowing the tapping of trachytic magma from the pre-Onano main Latera reservoir, concomitant to the mafic magma. The pseudo-rigid behaviour of the chamber wall rocks possibly caused a sudden drop of the confining pressure leading to extensive magma vesiculation and fragmentation. D) In the waning stages of the eruption, lowered magma pressure and the disrupted magma chamber roof allowed groundwater from the confined carbonate aquifer to interact explosively with the residual magma. Pulsating hydrostatic vs. magma pressure produced alternating hydromagmatic pyroclastic surges, strombolian scoria fall-out and spatter flows result a new structural rim developed close to the present-day eastern morphological rim of Latera Caldera. Although clear structural evidence is lacking, the decentralised magma withdrawal likely induced tilting of the old caldera floor to the east (trapdoor-style subsidence; Lipman 1997). Typically, trapdoor subsidence is related to asymmetric magma chambers, relatively small magma withdrawals and strong influence of substrate tectonics, resulting in asymmetric calderas that lack a true ring fault system beyond the occurrence of tensional fractures along their margin (Lipman 1997). This would be consistent with dyke emplacement along the new caldera margin in the final Onano eruption stage.

According to models of pressure evolution during caldera-forming eruptions, once collapse has begun the chamber roof is supported by the magma, causing renewal of magma pressure at the chamber roof to lithostatic (Scandone 1996, Martì et al. 2000). Subsidence of the chamber roof compresses the remaining magma, causing re-dissolution of the volatile component, inhibiting complete magma vesiculation (Martì et al. 2000), and leading to a rapid waning in the rate of magma discharge during late eruptive stages (Scandone 1996). This should be recorded by a progressive decrease in the degree of vesicularity of erupted products upsequence. In the case of the Onano eruption, however, an abrupt change in vesicularity occurs at the *lower spatter-upper lithic-rich breccia* transition, leading to a marked increase in juvenile clast vesicularity upward in the lithic-breccia (Fig. 6). Overall, relatively poorly fragmented and poorly vesicular spatter deposits (*lower spatter*) pass upward into the main pyroclastic flow deposit (*upper sillar*) which is rich in ash (highly fragmented) and juvenile vesicular pumice clasts.

Therefore, the problem is to explain increasing magma vesiculation and fragmentation and mass eruption rate in the eruptive phase following the onset of caldera collapse. Possible blocking of subsidence of the partially disrupted magma chamber roof may have occurred due to accommodation space problems related to a collapse geometry controlled by the presence of direct substrate faults within an horst and graben pattern, as shown by subsurface geology (Barberi et al. 1984). This may have caused a sudden drop of the confining pressure and consequent magma overpressure ($P_{lithostatic} << P_{magma}$), leading to extensive magma vesiculation and fragmentation.

Perrotta and Scarpati (1994) proposed arching of the roof as a triggering mechanism for rapid fragmentation of the poorly vesiculated top of the magma chamber, leading to eruption of spatter- and lithic-rich pyroclastic flows during the Breccia Museo eruption from the Phlegraean Fields. Roof arching, however, may not be necessary to explain the lithostatic pressure drop and increasing vesiculation in the magma chamber. Pseudo-rigid behaviour of the wall rocks is likely during rapid drainage of the chamber (Scandone and Giacomelli 2001). The widening and growth of the vent system concomitant with caldera collapse during the Onano eruption may have caused sudden decompression at the periphery of the magma chamber. The readjustment of the magma chamber walls with a pseudo-rigid behaviour led to an increasing magma discharge rate (Scandone and Giacomelli 2001). This triggered the climactic phase of the Onano eruption during which lithic debris produced by the collapse of the chamber roof was erupted to form the *upper lithic-rich breccia* and enhanced magma vesiculation and fragmentation produced the main pyroclastic flow (*upper sillar*).

In this phase, the feeder conduit system growth made possible the withdrawal of a residual batch of differentiated magma, represented by trachytic pumice in the matrix of the *upper sillar*, from the main Latera reservoir located beneath caldera centre, concomitant with the mafic magma batch from the peripheral reservoir, represented by coexisting black spatter clasts, which are shoshonitic to phonotephritic in composition. The contact between the two magmas may have acted as an additional trigger for the highly explosive character of this eruption stage.

The subsequent lowering of magma pressure and the disrupted magma chamber roof allowed external water from the carbonate aquifer to gain access into the magma reservoir to interact explosively with the residual magma. For the first time in the history of the Latera Volcanic Complex hydromagmatism occurred on a large scale. This is attributed to the availability of groundwater in the carbonate high below the eruption site, the mafic magma composition and the comparatively low mass eruption rate of the Onano event with respect to older, essentially magmatic, explosive eruptions of higher magnitude. Fluctuating hydrostatic vs. magma pressure ratio controlled the waning stages of the eruption, resulting in a thick succession of alternating hydromagmatic pyroclastic surge, strombolian scoria fall and minor spatter flow deposits (*hydromagmatic* and *strombolian deposits* and *upper spatter* units). Finally, the extrusion of a relatively degassed residual magma formed a lava ridge and dykes and a spatter cone along inferred eruptive fissures (i.e., La Montagna).

Conclusions

The Onano eruptive succession reveals the complex interplay between eruptive and collapse dynamics during caldera-forming events with implications for the interpretation of similar examples which are thought to be common in caldera environments (e.g., Phlegrean Fields and Santorini). The studied succession shows evidence of multiple changes of eruptive regime and emplacement modes which likely occurred during a single eruptive event. These include: early ash-pumice flow generation; energetic fire-fountaining producing spatter-rich flow (and subordinate fall) deposits; lag breccia and associated pyroclastic flow generation during the climactic phase of the eruption; alternating hydromagmatic and strombolian activity producing pyroclastic surge and scoria fall horizons, respectively, with concomitant spatter flow generation, in the final eruptive stages.

By contrast with previous large eruptions from the central vent area of the Latera Volcanic Complex, the Onano eruption site was located in a structurally weak area between the eastern rim of the pre-existing Latera caldera and the western margin of Bolsena volcano-tectonic depression. Intersecting rim fault systems favoured the ascent and eruption of a relatively mafic magma batch.

Magma vesiculation/fragmentation and discharge rate, and consequent eruptive style, were controlled by pressure evolution in the magma chamber and changing vent geometry related to caldera collapse. The enhanced magma vesiculation and fragmentation following the onset of caldera collapse is attributed to an open vent system causing a sudden drop of lithostatic pressure well below magma pressure. Two additional factors related to the widening of the feeder conduit system accompanying collapse may have enhanced late-stage explosivity: i) interaction of the mafic magma with a batch of differentiated magma tapped from the main reservoir located beneath the older caldera; ii) explosive interaction of magma with external water as migrating magma conduits intersected the carbonate aquifer.

Our interpretation of subsurface geology data differs from previous work (Barberi et al. 1984) in that the older caldera structure predating the Onano eruption is linked to the early explosive activity of the Latera Volcanic Complex (e.g., Canino, Farnese and Sovana eruptions; 0.3–0.2 Ma, approximately) rather than to the much older explosive activity that produced the so-called "basal ignimbrites", which are now attributed to the Paleovulsini Volcanic Complex (Vezzoli et al. 1987). We conclude that a late collapse phase occurred during the Onano eruption, involving the eastern part of the pre-existing Latera caldera and nearby extra-caldera volcano slopes. Interacting Latera and Bolsena volcano-tectonic systems governed site and style of the eruption, as well as of a stage of incremental caldera collapse. Although the Onano eruption was a relatively small-volume event, it produced shallow subsidence of the peripheral sector above the sedimentary substrate high, bringing Latera Caldera close to its present-day size. Subsidence likely occurred in a trapdoor fashion over a ~(2×5) km^2 sector, with a collapse height of ~0.2 km to the east, broadly compatible with the erupted volume of magma.

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