Phreatomagmatic volcanism in complex hydrogeological environments: La Crosa de Sant Dalmai maar (Catalan Volcanic Zone, NE Spain)

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ABSTRACT

The volcano of La Crosa de Sant Dalmai is a roughly circular asymmetrical maar that forms part of the Catalan Volcanic Zone (Girona Province, NE Spain). The edifice is an example of a maar-diatreme volcano constructed on a mixed basement of hard Paleozoic granites and schists and soft Pliocene and Quaternary deposits. The heterogeneities and differences in these rocks’ hydraulic properties and fracturing patterns influenced the way in which the magma-water interaction took place during the eruption and, consequently, the style of the eruption and the resulting deposits. The eruption of La Crosa de Sant Dalmai consisted of four consecutive eruptive phases characterized by alternating phreatomagmatic and magmatic fragmentation. The eruptive sequence and the variety of deposits—mainly fallout with subordinate surges—generated by this single eruption are a stark contrast to the compositional monotonity of the magma, which thus highlights the role played by the geological and hydrological characteristics of the substrate in determining the eruptive style and associated hazards in this type of volcanism.

INTRODUCTION

Maar-diatreme volcanoes are typical products of phreatomagmatism (e.g., Fisher and Waters, 1970; Lorenz, 1973, 1974, 1986; Fisher and Schmincke, 1984). They represent one of the most interesting examples of the explosive excava-

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The total volume of extruded magma in each eruption was small (0.01–0.2 km$^3$ dense rock equivalent [DRE]), suggesting that the amount of magma available to feed each eruption was also very limited. Strombolian and phreatomagmatic episodes alternated in most of these eruptions and gave rise to complex stratigraphic sequences displaying a wide range of pyroclastic deposits (Martí et al., 2011).

With a diameter of 1200 m, the maar of La Crosa de Sant Dalmai is the largest edifice in the Catalan Volcanic Zone. It belongs to the Garrotxa Volcanic Field (0.6–0.01 Ma), which includes the youngest volcanoes in the Catalan Volcanic Zone (Fig. 1). This volcano is located at the northern border of La Selva graben, a Neogene tectonic depression bounded by ENE-WSW– and NW-SE–oriented normal fault systems that affect the Paleozoic basement, and it is infilled with Pliocene and Quaternary sediments (Fig. 1).

La Crosa de Sant Dalmai is an example of a maar-diatreme volcano consisting of a circular tephra ring, 30 m and 50 m high on its eastern and western sides, respectively. Volcanic deposits cover an area of 7 km$^2$, extending up to 4 km eastward but only a few hundred meters westward (Fig. 2). Geophysical studies (Bolós et al., 2012) have found that La Crosa de Sant Dalmai developed on a NW-SE–oriented fault through which deep magmas were transported to the surface. This maar volcano is mostly composed of phreatomagmatic deposits with subordinate Strombolian phases. La Crosa de Sant Dalmai eruption ended with the formation of a scoria cone in the northern part of the main maar crater (Fig. 2). This small edifice emitted a basaltic lava flow that flowed southward and filled much of the maar crater (Bolós et al., 2012). Currently, postvolcanic lacustrine sediments cover this lava flow. The age of this volcano is not well constrained, but stratigraphic relations and existing U-Th and C$^{14}$ ages of the lava flow and posteruptive sediments suggest that it dates from the end of the Quaternary age.

**METHODS**

An important part of the research was carried out in the field in an area of ~10 km$^2$ surrounding the edifice of La Crosa de Sant Dalmai using as a reference the geological map produced by Bolós et al. (2012). In total, six stratigraphic sections were carefully studied. The stratigraphic criteria used to distinguish the different units forming the succession of volcanic deposits included color, nature and relative content of the components, and variations in grain size, texture, and sedimentary structures. Estimates of grain size were conducted partially in the field using a comparative grain size chart and then completed in the laboratory.

Grain-size analyses consisting of dry-sieving techniques, and componentry analysis were performed by weighing/counting 47 representative samples of the identified units. Large boulders were not considered for sieving but were measured and considered as part of the stratigraphic column for comparison with other layers. Samples were sieved with a set of sieves with a mesh size ranging from –6φ to +4φ units (64 to 1/16 mm). Grain-size data were used to define the median diameter ($Md_φ$) and sorting ($σ_φ$) (Inman, 1952) to help discriminate between deposits emplaced by fall and flow mechanisms. Clast compositions were characterized immedi-
stored outcrops are also shown (numbers). The extent of the phreatomagmatic deposits and the pre- and postvolcanic deposits. The studied outcrops are also shown (numbers).

Figure 2. Google Earth image and geological map of the volcano of La Crosa de Sant Dalmai (modified from Martí et al., 2011) showing the main crater and the inner scoria cone, as well as the extent of the phreatomagmatic deposits and the pre- and postvolcanic deposits. The studied outcrops are also shown (numbers).

CHARACTERISTICS OF THE PYROCLASTIC SUCCESSION

In order to reconstruct the complete succession of deposits, we carried out a detailed characterization of six stratigraphic sections in which six different facies were identified (Fig. 3). The lateral correlation of individual beds was possible using stratigraphic markers (Fig. 3); the maximum thickness of the observed succession was ~20 m (column 1, Fig. 3).

Facies Analysis

Facies SDA: Large Lithic Ballistic Deposits

This facies (Fig. 4A) has a maximum thickness of 200 cm (Fig. 3). It is clast supported and well sorted (e.g., samples SD1–1E, SD1–19E, SD2–1, SD3–2D; Fig. 5), with block- and lapilli-sized angular prevolcanic accidental lithic clasts (up to 70%; Fig. 3), as well as poorly vesiculated scoria fragments (Fig. 6A) and a scarce interstitial matrix of juvenile coarse lapilli-sized to coarse ash-sized clasts and the same prevolcanic accidental lithic clasts. The largest lithic clasts—up to 70–80 cm in diameter (Fig. 5)—are horizontally aligned and mainly correspond to granites and schists; they are subangular in shape, and some have partly or totally oxidized surfaces. Subordinate bombs of the same size are also present.

Facies SDB: Clast-Supported Deposits

The deposits of this facies (Fig. 4B) have a maximum thickness of ~300 cm (Fig. 3). They are clast supported and medium to well sorted (e.g., samples SD1–3CG, SD1–20, SD2–1B, SD2–5AB, SD2–7A, SD3–4G; Fig. 5), and they have coarse lapilli-sized fragments of poorly vesiculated scoriae (Fig. 6A) and granite and schist lithic clasts, with an interstitial matrix of lapilli and coarse ash fragments of the same composition. The largest clasts have a maximum size of 50 cm (Fig. 5). Facies SDB looks very similar to facies SDA (Fig. 4B), but it is characterized by a different percentage of nonvolcanic lithic clasts (up to 50%) compared to facies SDA (up to 70%; Fig. 3), and by poor stratification.

Facies SDC: Scoriaceous Clast-Supported Deposits

This facies (Fig. 4C) has a maximum thickness of 70 cm (Fig. 3). Its deposits are clast supported and moderately to well sorted (e.g., samples SD1–5AS, SD2–15B; Fig. 5) and have vesiculated scoria (up to 70%; Fig. 3) the size of coarse lapilli (Fig. 6C), as well as granite and schist lithic clasts with a maximum size of 40 cm (Fig. 5) and an interstitial matrix mainly consisting of juvenile fine lapilli and coarse ash fragments. Impact structures are generally absent. These deposits are characterized by normal and reverse grading.

Facies SDD: Scoriaceous Deposits

This facies (Fig. 4D) occurs in the middle of the sequence, where it reaches a maximum thickness of 250 cm (Fig. 3) and also corresponds to the last episode of the eruption, which led to the formation of a Strombolian cone (Fig. 2). No deposits directly connected to the scoria cone located inside the crater were present in the studied sections. The facies mantles the topography and consists of black-and-red, well-vesiculated bombs and lapilli scoriae (Fig. 6D) covered by a subordinate fine lapilli and coarse ash matrix. These deposits are generally well sorted (e.g., samples SD1–18E, SD3–2AI; Fig. 5). A few accidental lithic (granites and schists) clasts with a maximum size of 10–15 cm are found at certain levels (Figs. 4D and 5).

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Stratigraphic Units and Facies Associations

Four stratigraphic units (Figs. 2, 3, and 7) can be described from the study of the facies associations, each of which represents a successive stage in the construction of the volcano (Fig. 3). Unit I is represented by the lithofacies association I (facies SDA-SDB-SDC-SDE-SDF). Its thickness varies from 11 m in the western section (column 1, Fig. 3) to only 3 m in the east (column 6, Fig. 3). It is dominated by clast-supported deposits with relatively minor intercalated layers of lapilli-size material. The base of this unit is only visible in a few outcrops (columns 3, 5, and 6, Fig. 3), and it has thick layers of lithic-rich, fine lapilli (facies SDE) that correspond to the beginning of the eruption. On the eastern side, this initial deposit is overlain, in almost all the outcrops, by a series of thick deposits of coarse angular to subangular, lapilli-sized clasts (facies SDB) alternating with thin layers, just a few centimeters thick, of lapilli-sized clasts (facies SDE and SDF).

The following clast-supported, well-sorted deposit (facies SDA), with decimetric angular prevolcanic accidental lithics, is a good stratigraphic marker found throughout almost all of these outcrops (Fig. 3). A monotonous sequence characterized by facies SDB, facies SDC, facies SDE, and facies SDF completes unit I. In the eastern section (column 3, Fig. 3), the sequence is characterized by thin, bedded deposits of fine and coarse lapilli-sized clasts (facies SDE). Unit II (lithofacies association II, facies SDD) is represented by deposits that are almost 3 m thick in section 3 (Fig. 3) but that overall decrease to 1 m (column 1, Fig. 3) or less (column 2, Fig. 3). The unit is made up of highly vesiculated bombs and scoria lapilli with a certain percentage (up to 30%; Fig. 5) of accidental lithic clasts in certain levels.

Unit III is somewhat similar to unit I, and it is composed of the lithofacies association III (facies SDA-SDB-SDC-SDE-SDF). All the stratigraphic logs (Figs. 3 and 7) have a similar pattern. Their thickness varies from 8 m to less than 1 m (Fig. 3). This unit begins with a breccia (facies SDA) that has the same grain size as unit I and large blocks of accidental lithic clasts up to 70 cm (Fig. 5). The following deposits are dominated by thick, coarse layers of lapilli-sized breccia with accidental lithics up to 30 cm and nonvesiculated (juvenile) scoria (facies SDB), and occasional deposits with more vesiculated juvenile scoriae (facies SDC), intercalated with a small proportion of...
Figure 4. Field photographs of the characteristic facies of the maar of La Crosa de Sant Dalmai: (A) Facies SDA: block- and lapilli-sized angular prevolcanic accidental lithic clasts (AG, G, and S) and poorly vesiculated scoriae (SC); (B) facies SDB: clast-supported, medium to well sorted, with coarse lapilli consisting of poorly vesiculated lithics (AG, G, and S); facies SDB resembles facies SDA closely but has a different percentage of lithics (up to 50%); (C) facies SDC: clast-supported deposits with coarse lapilli consisting of vesiculated scoriae (SC) and subordinate lithics (G and S) in a mainly juvenile matrix with fine lapilli and coarse ash; (D) facies SDD: angular- to fluidally shaped, black-and-red, well-vesiculated bombs and lapilli scoriae, where I and II represent lithic-rich levels (delimited by yellow dotted lines), and III represents the lithic-rich transitional upper part toward the following breccia deposit; (E) facies SDE: thinly bedded, poorly vesiculated fine scoria lapilli with subangular accidental lithics, where the bed surfaces show planar and low-angle cross-stratified laminations and basal erosional contact; and (F) facies SDF: poorly sorted deposits with coarse, poorly vesiculated scoria lapilli and accidental lithics, where the bed surfaces show a diffuse stratification. AG—altered granite, G—granite, S—schists, SC—scoriae. Dashed red lines represent the facies limits.

Thin fine lapilli layers with planar stratification (facies SDE). Unit IV corresponds to a small scoria cone with an associated lava flow formed inside the maar (lithofacies association IV-SDD).

No evidence of stratigraphic discontinuities was observed in the sequence, and in some cases, slightly diffused contacts were observed among the different facies (Fig. 4). Mantle-derived nodules in the juvenile fragments are present in all of the units.

GRAIN SIZE, MODAL VARIATIONS, AND LITHIC DISTRIBUTION

Grain Size and Modal Variations

Vertical variations in the grain-size distribution and modal variations were analyzed by selecting representative samples from both the coarse- and fine-grained layers (Fig. 5). The maximum clast size is related to the energy conditions and efficiency of magma fragmentation, vent excavation, ejection, and emplacement. In the lowermost unit (unit I), fine layers dominate in the first part, with a general increase in grain size up to the first lithic-rich breccia. A general trend of alternating, well-sorted coarse lithic-rich lapilli deposits and poorly sorted fine lapilli deposits characterizes the first unit. As shown in Figure 5, the largest blocks measure up to 50–70 cm. Unit II includes coarse juvenile fragment-rich layers. Unit III is similar to unit I and is dominated by coarse deposits, particularly in the lower half of the unit, and a grain size that gradually decreases toward its upper part. Both units show the same characteristics and can be distinguished by being above or below unit II, which is an important stratigraphic marker of the eruption. Although the distribution of large blocks is variable, units I and III clearly include the largest proportion of blocks of the whole sequence.

Based on the grain-size data, Inman parameters (Inman, 1952) of median diameter ($Md_\phi$) and sorting ($\sigma_\phi$) were obtained and plotted on frequency histograms (Fig. 8) in order to help discriminate between fall and surge deposits. Sorting ($\sigma_\phi$) values for La Crosa de Sant Dalmai samples range between 1.5 and 2.25$\phi$, while the median diameter $Md_\phi$ values generally range between −4.3$\phi$ and −0.2$\phi$ (Fig. 8).

Componentry Analysis

La Crosa de Sant Dalmai deposits consist of a mixture of juvenile scoria and accidental lithic clasts in differing proportions (Figs. 3 and 5 and the Supplemental Figure1). Juvenile fragments are fresh, black, dense or vesicular scoria with a basaltic composition. The lithic fragments found in the different beds throughout the succession include granite and schist from the Paleozoic basement, as well as the same type of fragments—but with a different grade of roundness—from the Pliocene–Quaternary sediments that fill La Selva depression. These latter fragments were formed by the erosion and reworking of the Paleozoic basement. Although the juvenile material is present at all stratigraphic levels, its distribution is variable (Figs. 3 and 5).

1Supplemental Figure. Lithics content of addition- al samples from the composite stratigraphic columns shown in Figure 5. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00959.51 or the full-text article on www.gsapubs.org to view the Supplemental Figure.
Figure 5 (on this and following page). Composite stratigraphic column of the three main outcrops in La Crosa de Sant Dalmai. The lithics contents of the main samples are shown, and vertical variations in the maximum diameter of the lithic and scoria clasts are also indicated. (a) Facies SDA; (b) facies SDB; (c) facies SDC; (d) facies SDD; (e) facies SDE; (f) facies SDF; (g) Pliocene–Quaternary basement; (h) Paleozoic basement. (1) No componentry; (2) Pliocene and Quaternary lithic clasts; (3) metamorphic lithic clasts; (4) altered lithic clasts; (5) granite lithic clasts; (6) juvenile clasts.
Figure 5 (continued).
Small systematic variations in the occurrence of the lithic fragments can be seen in the stratigraphic succession. The lower part of unit I is characterized by a breccia deposit (e.g., sample SD1–1E; Fig. 5) with angular lithic fragments, mainly granites and schists (up to 40%), and Pliocene–Quaternary fragments (around 15%) with subordinate altered clasts (~10%). The whole of unit I is dominated by alternating coarse-grained deposits (e.g., samples SD1–3CG, SD2–1B, SD2–5AB; Fig. 5) that contain ~45%–50% juvenile lithic clast fragments (10% of Pliocene–Quaternary fragments, less than 5% of altered clasts, and around 40% of fragments from the Paleozoic basement), as well as fine lapilli deposits (e.g., samples SD1–2, SD1–14, SD3–1B; Fig. 5) with lithic fragment contents of around 30%–40%. Only a few levels (e.g., sample SD1–5AS; Fig. 5) of unit I are dominated by juvenile material with lithic fragments reaching 20%–30% in abundance (with less than 5% of Pliocene–Quaternary lithics clasts). The highest proportion of juvenile clasts is found in unit II, where the accidental lithic fragments from the Paleozoic basement represent less than 1% (e.g., samples SD1–18E, SD3–2AI; Fig. 5). However, some levels in unit II show a notable increase in granite and schist fragments (up to 30%) and a very high content of altered clasts and metamorphic fragments with almost no Pliocene–Quaternary content (e.g., samples SD1–18F; Fig. 5). In unit III, the same trends as in unit I are present. The sequence starts with a lithic-rich breccia with a lithic content of 50%–60% (mainly from the Paleozoic basement; e.g., samples SD1–19E, SD2–1, SD3–2D; Fig. 5) and continues with the same alternating succession as in unit I, with a variable amount of lithic clasts (20%–40%), which mainly originate from

Figure 6. Photographs comparing the juvenile fragments of different lithofacies: (A) facies SDA; (B) facies SDB; (C) facies SDC; (D) facies SDD; (E) facies SDE; and (F) facies SDF. Most of the samples are made of poorly vesiculated scoriae except that in D, which represents a pure Strombolian deposit (facies SDD).
Figure 7. The three main outcrops (1, 2, and 3) showing the main characteristics of the La Crosa de Sant Dalmai sequence. I, II, and III refer to the different units of the eruption, and the green letters represent the facies as shown in Figure 4.

Figure 8. Sorting ($\sigma_\phi$) versus median diameter ($Md_\phi$) plot of grain-size data from the fall and surge deposits. Dotted line defines samples from surge deposits, while continuous line shows samples from fall-out deposits.
the Paleozoic basement (e.g., samples SD1–20, SD2–7A, SD3–4G; Fig. 5) and with lesser amounts of Pliocene–Quaternary lithics (~5%). Unit IV is represented by a scoria cone (Fig. 2) largely made up of juvenile scoria fragments.

**LITHOLOGICAL AND HYDROGEOLOGICAL CHARACTERISTICS OF THE PREVOLCANIC SUBSTRATE**

The maar of La Crosa de Sant Dalmai is located on the northern border of the La Selva Basin on the fault contact between the Paleozoic basement and the Pliocene–Quaternary sediments that fill the depression (Bolós et al., 2012). La Selva Basin covers an area of 565 km² and is located in NE Catalonia (Fig. 9). It has a graben structure (Pous et al., 1990) and is bounded on four sides by mountain ranges with greater relief, including the Guillerias range to the west, the Transversal range to the north, the massifs of Gavarres to the east, and the Selva Marítima mountains to the south. This basin was created during the Neogene extensional period following the Alpine orogeny. Two main watersheds in the area correspond to the basins of the Santa Coloma and Onyar Rivers (Fig. 9). The Santa Coloma River Basin extends along the whole southwestern side of La Selva Basin and part of its headwaters are in the Montseny-Guillerias Mountains (Fig. 9). The Onyar River basin, on the other hand, occupies the northeastern side of the basin (Fig. 9) and has its headwaters in the Gavarres and Selva Marítima ranges. As proposed by Menció (2005) and Folch et al. (2011), three main hydrogeological units are present in La Selva Basin (Figs. 9 and 10): (1) alluvial materials, surface Neogene sedimentary layers, and highly porous and permeable weathered igneous rocks; (2) layers of arkosic sands, gravels, and conglomerates with a low clay content and Neogene sediment alternating with layers of low-permeability clays and silt, which compose the main infilling in this basin (where the transmissivity and permeability of the Neogene sediments are both very low; except for the conglomerate-rich levels); and (3) crystalline materials (Paleozoic igneous and metamorphic rocks), which generally have low permeabilities but also have a set of structural heterogeneities (fractures, schistosity, presence of dikes and alteration) that act as zones of preferential flow.

As proposed by Menció et al. (2010) (Fig. 9), based on hydrochemical and isotopic data, the general model for underground flow requires a local flow system generated by the subsurface topography of the basin that is related to the main alluvial aquifers and more superficial Neogene layers. Furthermore, a regional flow system runs across La Selva Basin, and its recharge zone is located in the adjacent massifs (the Guillerias and Transversal ranges and, to a lesser extent, in the Gavarres and Selva Marítima ranges). Piezometric data proposed by Folch et al. (2011) indicate the presence in the La Selva area of unconfined aquifers less than 30 m deep and confined or semiconfined aquifers over 30 m deep. Furthermore, based on hydrochemical and isotopic data, the same authors proposed a lateral hydraulic connection between the range-front areas and the basin aquifers, which would indicate an effective recharge through fault zones and fracture networks within the basin. Similar behavior is also suggested to occur at the contact between the sedimentary infill of the basin and the basement, with the magnitude of the recharge depending on distinct geological features such as the hydraulic conductivity of the lowest Neogene sediments, the thickness of the weathered granite on top of the basement, and the fracture network. At the same time, hydraulic head data indicate a vertical connection between sedimentary aquifer levels at various depths, which allows distinct vertical connections between the Neogene sedimentary aquifer layers (Folch et al., 2011). Additionally, hydraulic head records indicate that the regional hydraulic head decline due to water withdrawal is recovered annually despite the rainfall regime. This behavior is attributable to the effective recharge from the aforementioned regional flow system (Menció, 2005).

In general, the distribution of the water table is consistent with the topography of the area. The western, eastern, and southeastern areas of La Selva Basin are characterized by a steep gradient (coincident with the mountainous areas of Guillerias, Gavarres, and Selva Marítima), while in the central part of the basin, the distance between the isopieces (equipotential curves representing the phreatic surfaces of the aquifer) grows, and the gradient decreases (Menció, 2005).

**DISCUSSION**

The eruption of La Crosa de Sant Dalmai included episodes that were clearly dominated by a magma-water interaction and magma-poor phases as shown by field evidence (Fig. 4), the abundance of lithics fragments (Figs. 3 and 5 and the Supplemental Figure [see footnote 1]), and the general low vesicularity of the juvenile fragments (Fig. 6). The lithological and depositional characteristics (Fig. 4) as well as the granulometrical analysis (Fig. 8) of the resulting deposits reveal that most were formed by fallout mechanisms of ballistic blocks and bombs impact sags, and subordinate pyroclastic surges. The characteristics of the lithofacies and lithofacies associations, as well as the results of the componentry analysis, provide the necessary clues for understanding the evolution of the eruption and the construction of the volcanic edifice.

The sequence starts with lithic-rich fine lapilli layers (facies SDE) deposited by pyroclastic surges, as suggested by the presence of cross laminations (Fig. 4E). This first episode corresponds to an initial phreatomagmatic phase during which the efficiency in the energy transfer from the magma to the phreatic water was optimal, as indicated by the characteristic high degree of fragmentation in the resulting deposit. At this stratigraphic level, it is very likely that the locus of the explosions was located between the weathered surface of the granite basement and the Quaternary deposits (stage I, Fig. 10), as shown by the relative abundance of Quaternary fragments compared to the rest of the sequence (Fig. 5). The characteristics of these initial deposits and their radial distribution reflect the presence of a base-surge-type explosion (Crowe and Fisher, 1973; Fisher and Waters, 1970; Druitt, 1998), as has occurred at the beginning of other phreatomagmatic eruptions (e.g., Atexac crater [eastern Mexico], Carrasco-Núñez et al., 2007; Tihany [Hungary], Németh et al., 2001). The first episode was followed by the deposition of mainly lithic-rich fallout lapilli-sized clast layers (e.g., samples SD2–1B, SD2–5AB; Fig. 5). As proposed by Carrasco-Núñez et al. (2007), the deposition of these layers could have been associated with the formation of an ephemeral eruptive column. This vent-opening episode was immediately followed by the formation of a thick breccia deposit (facies SDA), with abundant angular lithic clasts of block and lapilli size, derived from the mixed (Paleozoic and Pliocene–Quaternary) substrate rocks, and poorly vesiculated scoria fragments (Fig. 6A). This breccia corresponds to the main vent-enlargement phase caused by a major influx of phreatic water into the eruption conduit. The largest clasts, mainly granites and schists, are horizontally aligned and did not generate impact structures. Martí et al. (1986) suggested that this breccia originated from a very shallow explosion that generated ballistic trajectories with an important lateral component. Following this major explosive phase, a thick sequence formed the rest of unit I, dominated by poorly stratified, clast-supported deposits (facies SDB; Fig. 6B) alternating occasionally with deposits of more vesiculated scoriae (facies SDC; Fig. 6C) and diffusely stratified deposits of lapilli-sized clasts (facies SDF, Fig. 6F) and subordinate thinly bedded deposits (facies SDE; Fig. 6E).
Figure 9. Geographical and geological setting of La Selva Basin, with the watershed boundaries with the two main subbasins (Onyar and Santa Coloma Rivers) marked. Arrows indicate the recharging area of the basin (modified after Folch et al., 2011). The A–A′ profile consists of a block diagram showing the general hydrogeological characteristics of the substrate below La Crosa de Sant Dalmai and La Selva depression and the infilling of the tectonic graben of La Selva Basin and the crystalline materials (igneous and metamorphic rocks). The orthophoto was provided by ICC (UTM 31N-ED50 Institut Cartogràfic de Catalunya, 2013, www.icc.cat).
Figure 10. Four stages of the evolution of La Cosa de Sant Dalmai edifice: Stage 0—formation of La Selva Basin with the associated aquifers; Stage I—interaction of the ascending magma with the shallower Quaternary and Paleozoic altered granite aquifers; Stage II—first magmatic phase, probably due to a general decreasing of the water content in the shallower aquifer; Stage III—decrease in the fragmentation level in the conduit and a new phreatomagmatic episode in a deeper aquifer; Stage IVa—pure Strombolian phase, with the rise and eruption of the magma and no interaction with the probably almost exhausted aquifer; Stage IVb—emplacement of a lava flow inside the maar crater.
We suggest that the whole of unit I derived from explosions occurring in the weathered granitic basement, which would have contained abundant water (stage I, Fig. 10). This idea is supported by the large proportion of basement-derived granite and schist clasts in the beds that form this part of the succession (Fig. 5). Presumably, the rising magma would have occupied existing fractures in the granite and schist that would have probably filled with water. The lack of interaction with the first aquifer could be related to a high and rapid input of magma, as suggested by the presence of large mantle-derived nodules in the deposits, which would not have allowed the required energy transfer efficiency to permit magma-water interaction.

Facies SDA, SDB, and SDC suggest fallout and ballistic emplacement (Fig. 8; see Németh et al., 2001). In particular, facies SDC includes some horizons of juvenile scoria lapilli with few prevolcanic lithics fragments (Fig. 5), probably indicating episodes involving less water recharge from the aquifer. Generally, these latter explosions did not have the same energy transfer efficiency during the magma-water interaction as during the first explosion, as shown by the abundance of breccia deposits. The stratified beds (facies SDE and SDF) could be interpreted as deposits originating from a high-concentration suspension with little tractional transport (e.g., Chough and Sohn, 1990).

These deposits, different that facies SDA–SDC, suggest other transport and depositional mechanisms, probably related to changes in the eruption dynamics caused by changes in the efficiency of the hydromagmatic fragmentation. The efficiency of hydromagmatic fragmentation and the corresponding eruption dynamics depend on the pressure differences between magma and water, the water-magma contact mode, and magma temperature and viscosity (Wohletz and Sheridan, 1983), as well as on the exact nature of the coolant (White, 1996). This implies that the eruption responsible for the construction of La Crosa de San Dalmai maar was continuous but included several pulses in which different types of deposits were formed.

Unit II reflects an important change in the eruption dynamics (stage II, Fig. 10). It is made of well-vesiculated (Fig. 6D) scoria bombs and lapilli (facies SDD) with a few (less than 1%; Fig. 5) accidental lithic clasts in some levels. This facies is the result of fallout deposition from Hawaiian-style fire fountains. The fact that this scoria deposit appears in stratigraphic continuity (as suggested by the absence of erosional surfaces) with pheomagmatic unit I and immediately precedes a new pheomagmatic episode (Figs. 4D and 7) indicates that, at this stage, the water supply from the aquifer located between the altered granites and the Quaternary sediments (stage II, Fig. 10) was not sufficient to sustain the phreatomagmatic interaction with the ascending magma.

Due to the effect of hydromagmatic eruptions, a large amount of water is vaporized, causing a large and almost instantaneous withdrawal of groundwater from the aquifer. A lowering of the water table can be expected if hydromagmatic activity lasts over a period of several days (Lorenz, 1986). As suggested by Németh et al. (2001), in a porous media aquifer, with lateral heterogeneities, water might not flow fast enough to the vent area to maintain the phreatomagmatic character of the eruption, despite the abundance of groundwater in the rest of the aquifer. Thus, the conditions for a purely magmatic eruption might be reached, and Strombolian explosions may occur.

Unit III (stage III, Fig. 10) started with a new breccia episode (facies SDA) characterized by abundant large heterolithologic blocks (up to almost 1 m in diameter) originating from the Paleozoic basement, and poorly vesiculated juvenile scoria (Fig. 6) resulted from the intermittent fallout deposition (facies SDB and SDC) and the subordinate pyroclastic surges (facies SDE and SDF). The lithic fragment contents, which mostly correspond to Paleozoic basement clasts with lesser amounts of Pliocene-Quaternary clasts (Fig. 5), indicate that the locus of the explosions migrated downward.

A possible water transmissivity is thought to occur at the contact between the sedimentary infill of the basin and the basement, although it would depend on hydraulic conductivity of the lowest Neogene sediments, the thickness of the weathered granite on the top of the basement, and the fracture networks. As the eruption progressed, the fracture-controlled aquifer could have been disrupted by the initial shock wave, causing an increase of secondary permeability and further excavation of the maar crater. This might have led to a decrease of the lithostatic pressure and a progressive lowering of the position of the fragmentation level in the eruption conduit during the course of the eruption (see Papale et al., 1998; Macedonio et al., 2005). This would have permitted a new pheomagmatic episode when the magma interacted with a deeper aquifer located in the fractured Paleozoic basement, as indicated by the nature of the lithic fragments included in unit III.

A second line of evidence of the existence of a deeper aquifer was provided by Menció (2005) and Folch et al. (2011) with field data, where multilayer aquifers were recognized in the La Selva area. Furthermore, investigations carried out by Folch and Mas-Pla (2008) highlighted the relevance of fault geometry upon the flow system and the connection between the upper basin-fill formations and the Paleozoic basement. Moreover, the same authors explained how some deep wells located close to La Crosa de Sant Dalmai area showed a confined type of behavior according to structural characteristics, fault geometry, and scaling. This might suggest a similar behavior for La Crosa de Sant Dalmai, enhancing the hypothesis of multilayer aquifers acting at different depth.

The eruption ended with a Strombolian episode (unit IV) (stage IV, Fig. 10) focused in the interior of the maar crater, which gave rise to the formation of a small scoria cone (stage IVa, Fig. 10) and the emission of a lava flow (stage IVb, Fig. 10) that was subsequently covered by lacustrine deposits. The transition from wet to dry conditions might suggest a significant decrease in the volumetric water content in the deeper levels of the aquifer as well as a changing water supply that thus ensured that the eruption would continue in a pure Strombolian phase. As suggested by Németh et al. (2001), a fracture-controlled aquifer might have a very strong seasonality, with an increasing or decreasing groundwater supply. Another hypothesis could suggest a magma conduit able to seal itself off from the surrounding aquifer, leading to a final purely magmatic phase.

The eruption sequence deduced for La Crosa de Sant Dalmai follows the generalized model proposed by Lorenz (1986). The proportion of lithic and juvenile fragments in the pheomagmatic deposits and the presence of pure Strombolian phases in the middle and at the end of the eruption suggest that water supply was not constant. Even assuming that magma supply was not continuous, the changes observed in the eruption sequence and the resulting deposits are better explained by changes in the water supply. This variation in the amount of water interacting with the erupting magma could be due either to the intermittent recharge of the aquifer during the eruption or to the magma interacting with a heterogeneous aquifer (in which the levels had different hydraulic characteristics) at different depths in the conduit. The first case would account for a relatively long eruption in which seasonal recharges of the aquifer could have induced this type of pulsating behavior. However, the eruption of La Crosa the Sant Dalmai seems to have occurred in a continuous fashion and over a short period of time, as is suggested by the absence of discontinuities in the stratigraphic sequence (Figs. 3 and 4). The intermittent magma-water interaction would thus seem to result from the interaction of the erupting magma with different aquifer levels located at different depths and with different hydrogeological properties, an explanation that matches
the hydrogeological characteristics of the study area. Alluvial and weathering materials with high permeabilities composing the main infilling deposits of La Selva Basin would have allowed the first phreatomagmatic phase, while the crystalline materials characterized by structural heterogeneities, enhanced by the presence of a fault system connected to La Selva Basin, would explain the second phreatomagmatic phase. Similar to La Crosa de Sant Dalmai, the same types of stratigraphic successions can be observed in other edifices of the Catalan Volcanic Zone. Martí et al. (2011) explained the differences in the eruptive behavior of the Catalan Volcanic Zone as related to the occasional interaction of the ascending magma with ground-water rather than to changes in magma composition rheology or magma supply.

The succession of deposits that form La Crosa de Santa Dalma is unique with stratigraphy all around the vent, albeit with smaller, thicker units and steeper angles in the west, and thinner units, gentler angles, and a broader distribution in the east, thereby suggesting a radial but asymmetrical distribution of the deposits (Fig. 2). This highlights the importance of differences in rock strength in mixed substrates, as already emphasized by Smith and Lorenz (1989), Sohn and Park (2005), and Auer et al. (2007) in other maar examples, which, in the case of La Crosa de Sant Dalmai (Bolós et al., 2012), made it easier for the phreatomagmatic explosions to excavate the eastern side where the soft Pliocene–Quaternary sediments were found. This is also suggested by the strong eastward horizontal component in the fallout deposits, which were probably influenced by this type of rheological contrast with the host rocks.

CONCLUSION

La Crosa de Sant Dalmai maar formed on the northern border of the Neogene La Selva Basin on a NW–SE–oriented normal fault that was probably used by deep magma to reach the surface. This maar volcano is an example of the way in which a tephra ring develops in a mixed setting characterized by a hard (Paleozoic granites and schists) and soft (Quaternary filling) lithology. We also suggest that a tephra ring develops in mixed substrates with heterogeneities and differences in the hydrogeological structure of the area, and aquifer levels with different hydraulic properties and fracturing patterns. These differences clearly influence the way in which the phreatomagmatic water interaction occurred throughout the eruption and, consequently, the style of the eruption and the resulting deposits. The eruption at La Crosa de Sant Dalmai included four eruptive phases with alternating phreatomagmatic and magmatic fragmentation. As occurs in many other volcanoes in the same monogenetic field, the eruptive sequence and resulting deposits that formed La Croa de Sant Dalmai contrast with the compositional monotony of the magma, thereby emphasizing the role played by the geological characteristics of the substrate in determining the eruptive style and associated hazards in this type of volcanism.

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