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Maars to calderas: end-members on a spectrum of explosive volcanic depressions

Danilo M. Palladino[1], **Greg A. Valentine**[2]*, **Gianluca Sottili**[3] and **Jacopo Taddeucci**[4]

[1] Dipartimento di Scienze della Terra, Sapienza-Università di Roma, Roma, Italy, [2] Department of Geology, University at Buffalo, Buffalo, NY, USA, [3] Istituto di Geologia Ambientale e Geoingegneria-CNR, Roma, Italy, [4] Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

We discuss maar-diatremes and calderas as end-members on a spectrum of negative volcanic landforms (depressions) produced by explosive eruptions (note—we focus on calderas formed during explosive eruptions, recognizing that some caldera types are not related to such activity). The former are dominated by ejection of material during numerous discrete phreatomagmatic explosions, brecciation, and subsidence of diatreme fill, while the latter are dominated by subsidence over a partly evacuated magma chamber during sustained, magmatic volatile-driven discharge. Many examples share characteristics of both, including landforms that are identified as maars but preserve deposits from non-phreatomagmatic explosive activity, and ambiguous structures that appear to be coalesced maars but that also produced sustained explosive eruptions with likely magma reservoir subsidence. A convergence of research directions on issues related to magma-water interaction and shallow reservoir mechanics is an important avenue toward developing a unified picture of the maar-diatreme-caldera spectrum.

Keywords: maar, diatreme, caldera, phreatomagmatic, explosive eruption

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Royal Holloway University of London, UK

***Correspondence:**
Greg A. Valentine,
Department of Geology, University at Buffalo, 411 Cooke Hall, Buffalo, NY 14260, USA
gav4@buffalo.edu

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Introduction

Maar-diatremes and explosive calderas are two types of volcanic depressions that cut into their pre-eruption landscapes (negative landforms), and are surrounded by low-profile accumulations of erupted material (note that non-explosive calderas, while important volcanic features, are not discussed here). Although superficially they can be similar except in size, our understanding of their origins developed along two largely independent lines of research. We discuss these as end-members on a spectrum of explosive volcanic depressions. The spectrum is defined by the relative importance of discrete explosions related to interaction of magma with phreatic water (phreatomagmatic) compared to subsidence due to magma withdrawal during sustained magmatic volatile-driven eruption. The common occurrence of intermediate or hybrid examples suggests links between magma-water interaction and calderas that are worthy of focused research by the volcanology community.

Characteristics of the End-members

We consider the idealized maar-diatreme end-member (also more simply called *maars* elsewhere in this paper; **Figure 1**, **Table 1**) to be the product of repeated, discrete explosions caused by

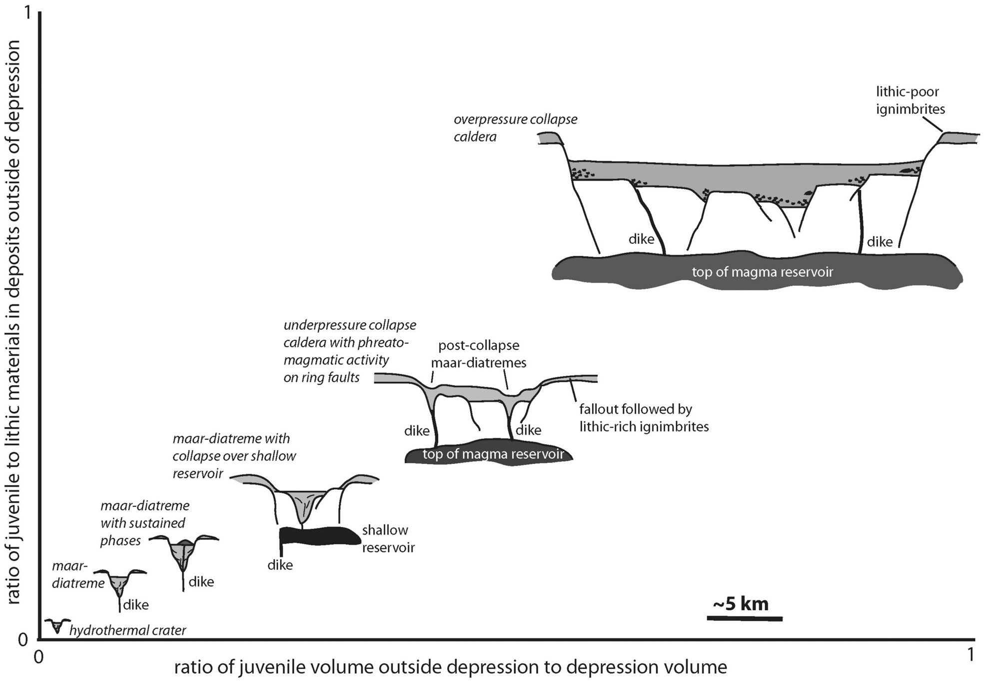

FIGURE 1 | Qualitative illustration of the spectrum of negative volcanic landforms produced by explosive eruptions, in terms of amount of juvenile material deposited outside the depression relative to lithic content and depression volume. Hydrothermal (phreatic) explosion craters are included in the diagram as extreme examples with no juvenile material, although strictly speaking they are not volcanic depressions even though they are commonly associated with volcanoes. Cartoon of *maar-diatreme with sustained phases* shows late-stage scoria cone in crater; although sustained, magmatic volatile-driven phases may also occur before and during phreatomagmatic activity. Cartoons, which are drawn approximately to scale, are intended to show the depressions just after formation, and thus do not show post-eruption sediments or caldera resurgent features. See **Table 1** for examples across the spectrum.

subsurface interaction of magma and groundwater, typically over time scales of a few days to a few years. Recent field and experimental studies of maars and their underlying diatremes show that subsurface explosions may or may not erupt onto the surface, depending upon their depths and energies; shallow explosions (upper ~200 m) are most likely to actually eject material, while deeper blasts brecciate magma and country rock and mix them through combined upward-directed debris jets and subsidence (e.g., White and Ross, 2011; Graettinger et al., 2014; Valentine et al., 2015). A tephra ring produced by this end-member type of activity will have many depositional units, corresponding to many explosions, and will be dominated by tuff breccias, stratified and cross-stratified lapilli-tuff beds produced by pyroclastic surges, ballistic bombs and blocks, and thin ash fallout beds. The deposits from individual explosions are strongly influenced by explosion energy-depth relationships and the effects of the developing crater on eruptive jets (Valentine et al., 2014; Graettinger et al., in press). Country rock lithic abundance will be high, approaching 100% in some units, in the tephra ring, and lithic clasts derived from progressively deeper levels may appear upward in the stratigraphy due to the subsurface explosive mixing. Most deposits extend no more than a few kilometers from the craters, which are typically ~500–1500 m in diameter, although larger ones can be produced due to lateral shifting of explosion sites (e.g., Jordan et al., 2013). The total erupted volume of magma may range to a fraction of cubic kilometer, or rarely a few cubic kilometers in case of polygenetic maars (**Table 1**). Maars are underlain by crudely funnel-shaped diatremes that typically extend hundreds of meters to ~2 km downward in the subsurface, eventually merging with a feeder dike(s). The diatremes include pyroclastic material deposited on the crater floor and subsided to depth (e.g., Delpit et al., 2014), massive tuff breccias and lapilli tuffs which often occur in subvertical cross-cutting domains and that have a wide range of juvenile and lithic clast proportions (e.g., Ross and White, 2006; Lefebvre et al., 2013), and small intrusions in a variety of forms (e.g., Valentine and van Wyk de Vries, 2014). Most maars are monogenetic, meaning that each formed during an individual eruptive episode with duration of days to years.

An idealized explosive caldera end-member (**Figure 1**; **Table 1**) forms by subsidence during withdrawal of a few to thousands of cubic kilometers of magma during sustained high-discharge-rate eruption. Some caldera-forming eruptions begin with sustained sub-Plinian to Plinian columns that decompress the magma reservoir, followed by sustained pyroclastic fountaining that feeds pyroclastic density currents from the developing ring faults as the caldera founders and collapses into the magma reservoir (underpressure calderas, **Table 1**; Martí et al., 2009; Palladino et al., 2014). Other calderas, especially the largest ones, form by extensive roof faulting due to

TABLE 1 | Volcanic depression types on spectrum from hydrothermal explosion craters to large explosive calderas.

Type	Life cycle	Processes	Key features	Examples
Hydrothermal explosion crater[a]	Days-months	Isolated or repeated discrete hydrothermal explosions with ballistic ejection of subsurface lithics and occasional hot mudflows. Erupted volumes $<<1$ km^3.	Depression from a few meters to 100s of m diameter (if explosion locations shift laterally) Occurrence in active hydrothermal systems (e.g., caldera floors) Ballistic apron extending up to 100s m from depression. No eruption of magma.	Nisyros (Greece; Marini et al., 1993) Te Maari (New Zealand; Lube et al., 2014)
Maar-diatreme (end-member)	Months-years	Numerous discrete phreatomagmatic[b] explosions at a range of depths. Depression formed by combined ejection of material and subsidence of diatreme fill. Erupted volumes <1 km^3.	Diatreme 100s of m to ∼2 km deep, contains small irregular intrusions, converges to feeder dike(s) Depression up to ∼1 km diameter (larger if vent locations shift laterally) Tephra ring lithic-rich and dominated by stratified, cross-stratified lapilli tuffs, massive tuff breccias, ballistics; most deposits extend less than ∼5 km from depression. Usually mafic magma composition. Poorly to moderately vesicular juveniles.	Stracciacappa maar (Sabatini, Italy; Sottili et al., 2012) Lunar Crater maar (Nevada, USA; Valentine et al., 2011) Teshim maar (Arizona, USA; White, 1991)
Maar-diatreme with juvenile-rich tephra beds	10^2–10^4 years	Same as above but with periods of sustained magmatic[c] activity (Strombolian to subPlinian) before, during, and/or after phreatomagmatic activity. Erupted volumes <1 km^3 or larger for multiple maars.	Diatreme same as above Depression same as above or more irregular due to coalescence, may have scoria cone or lava in crater if magmatic phase is late in eruptive episode Tephra ring same as above, but with juvenile rich lapilli and lapilli tuff fallout beds that may extend >10 km from depression. Mainly mafic magma composition. Poorly to moderately vesicular juveniles.	Purrumbete maar (Victoria, Australia; Jordan et al., 2013) Ukinrek maars (Alaska, USA; Self et al., 1980) Albano polygenetic (multiple) maar (Colli Albani, Italy; Giaccio et al., 2007)
Maar-diatreme with caldera component	10^2–10^4 years	Same as above, with significant sustained magmatic activity, and with addition of subsidence over shallow reservoir (sill) due to magma withdrawal. Erupted volumes up to ∼1 km^3.	Diatreme with possible additional subsidence features such as faults in surrounding host rock Depression up to ∼5 km diameter, with significant fault component Tephra ring dominated by fine-grained juvenile material, massive to stratified and cross-stratified lapilli tuffs, fallout beds, and ballistic blocks. Some massive lapilli tuffs may extend many km from depression. Mafic to silicic magma composition. Moderately to highly vesicular juveniles.	Baccano depression (Sabatini, Italy; Sottili et al., 2012) Agnano tuff ring (Campi Flegrei, Italy; Mastrolorenzo et al., 2001) Laacher See (Eifel, Germany; Freundt and Schmincke, 1986) Kefalos tuff ring (Kos, Greece; Dalabakis and Vougioukalakis, 1993)
Underpressure caldera collapse with widespread phreatomagmatic activity	10^4–10^5 years	Eruption dominated by sustained discharge of juvenile material, high eruption columns from early phases of eruption that decompress the reservoirs, and pyroclastic density currents. Main depression formed by subsidence over reservoir due to magma withdrawal. Abundant lithics incorporated into eruption during caldera collapse. Phreatomagmatic activity before, during, and/or after main magmatic episode and/or late evolutionary stage of the caldera. Erupted volumes several km^3 to a few 100 km^3.	Intracaldera ignimbrite interstratified with lithic breccias and megabreccias up to ∼2 km deep, fault-bounded subsurface structure; ring dikes, stocks, sills Depression up to ∼30 km diameter, mainly fault bounded. Post-caldera resurgent structures within larger calderas Deposits outside depression dominated by ignimbrites with lithic-rich proximal facies, and pumice fallout deposits, extending tens of km or more from caldera.	Latera Caldera (Vulsini, Italy; Palladino and Simei, 2005) Santorini Caldera (Greece; Heiken and McCoy, 1984)

(Continued)

TABLE 1 | Continued

Type	Life cycle	Processes	Key features	Examples
Overpressure caldera collapse (end-member)	10^5–10^6 years	Sustained discharge of juvenile material driven by magmatic volatiles, dominated by fountaining and pyroclastic density currents with minor fallout from eruption column. Erupted volumes exceed several 100 km^3. Phreatomagmatic components of eruptions minor.	Intracaldera ignimbrite interstratified with lithic breccias and megabreccias up to ~2 km deep, fault-bounded subsurface structure; ring dikes, stocks, sills Depression up to ~100 km diameter, mainly fault bounded. Post-caldera resurgent structures. Thick ignimbrites with minor fallout beds, extending up to ~100 km or more from caldera.	La Garita caldera (Colorado, USA; Lipman, 2000) Cerro Galan caldera (NW Argentina; Cas et al., 2011)

[a] *Hydrothermal explosion craters included for completeness although they are not volcanic craters in the strict sense of emitting magma.*

[b] *Phreatomagmatic is used here for explosions caused by interaction of magma and water mainly in subsurface.*

[c] *Magmatic is used here for eruptive activity driven primarily by magmatic volatiles, with little or no influence of groundwater or surface water.*

magmatic tumescence that triggers eruption of large pyroclastic density currents directly by fountaining and concurrent caldera collapse (overpressure calderas, **Table 1**; Martí et al., 2009; see also Gudmundsson, 1998). Deposits around calderas can include widely dispersed fallout beds, but the bulk of the products are usually preserved in ignimbrites that are relatively massive and poorly sorted. Juvenile components in the form of pumice (coarse-ash to block sizes) and vitric ash (medium to fine ash sizes) dominate the deposits. Although lithic-rich domains can be abundant in proximal facies (co-ignimbrite lag breccias; Druitt, 1985; Walker, 1985), in local concentrated zones, and as isolated clasts throughout the extent of an ignimbrite, the lithics are overall a minor component compared to juvenile particles. The ignimbrites may extend 10s to >100 km from the calderas, filling in topographic lows and smoothing the landscape. Calderas range from several kilometers to several tens of kilometers in diameter, with subsidence depths from a few 100 m to a few kilometers (Acocella, 2007). Beneath the surface expressions of calderas are thick accumulations of intracaldera ignimbrite, often exceeding 1 km thickness, with interstratified breccias and megabreccias associated with caldera collapse (Lipman, 1976, 1984). Intrusions include dikes, sills, and stocks. Many calderas, especially the larger ones, have some sort of structural or eruptive resurgence during the tens of thousands of years after collapse that results in a raised central portion (not shown in **Figure 1**). Most calderas are related to magmatic systems that have life spans of hundreds of thousands to a million years, and result from multiple, hours- to days-long caldera-forming eruptions. However, a given caldera forms during a single eruptive episode, as does a maar-diatreme (recognizing that many caldera clusters are the products of multiple, overlapping calderas formed during different episodes).

Both maars and calderas are produced by volcanic and hypabyssal intrusive processes, but typically also contain sedimentary deposits that are characteristic of steep-sided, closed basins.

Intermediate Examples

Many volcanoes that are identified as maars included eruptive phases with little or no involvement of external water, and with sustained discharge of mainly juvenile material. This magmatic volatile-driven activity may occur in either early or late phase of a maar-forming event, or may alternate repeatedly with phreatomagmatic phases (e.g., Houghton et al., 1999; Sottili et al., 2009; **Figure 1**, **Table 1**). Often it is preserved as scoria lapilli fallout horizons within tephra ring sequences, and can be traced to distances that exceed the main tephra ring deposits that were mainly emplaced by pyroclastic surges and ballistics. The fallout beds are characteristic of sustained Hawaiian, violent Strombolian to sub-Plinian eruption columns. For example, the ultrapotassic Albano multiple maar hosted repeated cycles of eruptive activity through 35 kyrs, reaching estimated maximum column height of 18–21 km (and corresponding peak magma discharge rate up to 2.6 × 10^7 kg/s), with erupted products requiring differentiation in a sizeable magma reservoir (Giaccio et al., 2007). Most volcanoes of this type involve relatively mafic magmas, for which the criteria to assess the phreatomagmatic vs. magmatic volatile-driven nature of associated deposits have been established in the literature (e.g., Heiken and Wohletz, 1985). In some examples scoria cones, produced mainly by Strombolian activity, and lavas are preserved on maar crater floors (e.g., La Crosa de Sant Dalmai maar, Spain; Bolós et al., 2012; Pedrazzi et al., 2014). These record ascent of magma batches through a diatreme with minimal interaction with groundwater; however, the main landforms—maars and tephra rings and underlying diatremes—were produced by discrete phreatomagmatic explosions. Although magmatic volatile-driven, sustained eruption played a role, these examples are near the maar end-member.

In other examples (**Table 1**), usually involving the eruption of more silicic magmas, sustained activity becomes more significant and may prevail even though their landforms are similar to those of end-member maar-diatremes. Commonly, trachytic and phonolitic examples in central Italy have tephra rings and maar-like craters, and their deposits are dominated by fine-grained, moderately to highly vesicular juvenile clasts and very few lithic clasts, most of which were emplaced ballistically. Except for the relatively fine-grained nature of the deposits, typical indicators of phreatomagmatic explosions and fragmentation, such as high lithic contents and blocky, poorly vesicular ash grains with quench cracks, may be lacking. This brings ambiguity to interpretation of magma fragmentation and eruption mechanisms. In many examples at Campi Flegrei, explosive interaction with external water (groundwater and/or surface water) has been inferred to involve an already vesiculated and partially fragmented magma (Mastrolorenzo et al., 2001). Silicic examples include both tuff ring and maar-like systems, such as Averno 2 in the Campi Flegrei (with 0.07 km^3 DRE of erupted products and peak mass discharge rate of 3.2×10^6 kg/s; Di Vito et al., 2010), comparable in scale with the Martignano center at Sabatini (Sottili et al., 2012); Toga tuff ring, Japan (Kazuhiko et al., 2002); and the Cerro Pinto tuff ring-dome complex, Mexico (Zimmer et al., 2010).

Wider depressions are transitional to calderas. For example, the Baccano depression (Sabatini Volcanic District, central Italy), ca. 4 × 3 km across, has been interpreted both as a composite maar with coalesced craters and as a small caldera (de Rita et al., 1983; Buttinelli et al., 2011; Sottili et al., 2012). Laacher See depression (Eifel, Germany), about 3 km in diameter, is identified by Freundt and Schmincke (1986) as a maar, despite the unusually high volume (16 km^3 of loose deposits) and dispersal of phonolitic tephra, and the dominance of deposits from inferred magmatic volatile-driven *vs.* phreatomagmatic processes.

Similarly, deposits associated with identified calderas often show some evidence of significant phreatomagmatic explosions. Detailed studies of eruptive products of calderas such as Askja (Iceland; Self and Sparks, 1978; Carey et al., 2009) and Taupo (New Zealand; Self and Healy, 1987; Houghton et al., 2010) reveal deposits that are inferred to have resulted from simple magmatic volatile-driven processes to interaction of vesicular (and already fragmented?) melt with externally derived water (phreatoplinian). In these and other cases, the presence of very fine-grained fallout beds with abundant accretionary lapilli might indicate water-assisted fragmentation, although there is uncertainty associated with the attribution of phreatomagmatic origin based mainly on the high degree of magma fragmentation (Palladino and Taddeucci, 1998; Dellino et al., 2001; Colucci et al., 2013). Some deposits at the bases of the main ignimbrites preserve evidence of phreatomagmatic explosions, such as high lithic contents and/or bed forms that indicate deposition from pyroclastic surges. Latera volcano (Vulsini Volcanic District, Italy) is an example that had several caldera-forming eruptions, each of which produced ignimbrites with volumes on the order of several cubic kilometers. All around the rim of its ∼9 ×7 km depression (except where buried by younger lavas) are stratified and cross-stratified tuffs and lapilli tuffs interpreted to be associated with discrete phreatomagmatic explosions and resulting pyroclastic surges. Such cases record volumetrically minor phases in individual caldera-forming eruptions that are otherwise dominated by sustained discharge of juvenile material (e.g., Onano eruption; Palladino and Simei, 2005), as well as widespread circum-caldera activity during the late evolutionary stage of Latera. The main process responsible for caldera formation in all of these cases was syn-eruptive subsidence over a large magma reservoir. Although phreatomagmatic activity played a role, these volcanoes are near the caldera end-member.

Perspectives on the Spectrum and Research Gaps

We suggest that it is important to think about maar-diatremes and explosive calderas in the context of a spectrum of behaviors. Such a framework highlights key problems that, from our perspective, should be major topics of research in the volcanological community.

We consider the idealized maar-diatreme end-member to be the result of discrete phreatomagmatic explosions in the subsurface caused by molten fuel-coolant interaction (MFCI), which involves premixing of melt and water (or slurry) followed by thermohydraulic detonation (Büttner and Zimanowski, 1998). MFCI is favored by: (1) low melt viscosity (mafic rather than silicic magmas) because a large viscosity contrast between melt and water acts against premixing; (2) small magma batches, which more easily premix and are emplaced rapidly into the hypabyssal environment with minimal time for degassing and crystallization; (3) low overall magma fluxes which favor the intrusion of small batches of magma and do not overwhelm available water; and (4) low melt vesicularity (Zimanowski et al., 1995), because the presence of compressible bubbles acts against the important process of magma fracture during rapid melt-water heat transfer, which is key in the thermohydraulic detonation phase of MFCI. The latter is assisted by low melt viscosity, which allows many bubbles to coalesce and even escape a magma batch, leaving sufficient "pure" melt for MFCI. All of these conditions are most likely to be met in small, monogenetic, mafic volcanoes and indeed most maars that approach end-member behavior are of that type. Valentine et al. (2014) suggested that most phreatomagmatic explosions in this context release mechanical energies in the range of 10^9–10^{12} J, and more likely toward the low end of that range. Mafic monogenetic volcanoes often do not have shallow magma reservoirs but are fed by magmas that ascend from depths of tens of kilometers to the surface, which reduces the role of surface subsidence due to magma withdrawal, although subsidence can occur by post-eruptive compaction of diatreme fill.

Explosive calderas involve large volumes of magma that evolves in long-lived crustal reservoirs with country rock roofs that subside, mainly bounded by faults (e.g., ring faults), as they are drained. Melt viscosity is normally relatively high, and bubbles that form as magma ascends are coupled with the melt, promoting in turn the formation of pumice and ash during sustained high-flux discharge that is very different from the discrete explosions caused by MFCI. All of these aspects in fact act against magma-water interaction within the context of MFCI, and we urge caution in applying concepts such as optimal magma-water ratios and the classical ash morphology criteria (e.g., Heiken and Wohletz, 1985) to examples that involve vesicular, viscous magmas and deposits that suggest high discharge rates. While MFCI may cause fine fragmentation of small batches of mafic magmas (which otherwise tend to produce scoria cones or lavas), can the process simply be "added" to volatile-driven vesiculation and fragmentation to produce additional fragmentation of silicic magmas and maar-like landforms? Is the process feasible up to phreatoplinian scale? Is magma vesiculation, which might reduce the magmastatic pressure at a given depth in a conduit (by reducing the mixture density) so that it falls below the local hydrostatic pressure, important in allowing for mixing of phreatic water into a conduit with active magma flow? Although extra fragmentation by interaction with externally derived water is often inferred (e.g., for phreatoplinian processes) we have essentially no experimental or theoretical basis for inferring subsurface or surface magma-water interaction under conditions of high magma flux, viscosity, and bubble content. This is a major and difficult-to-address gap in our understanding that deserves focused research.

Volcanic depressions that fall toward the middle of the spectrum (**Figure 1**) have different combinations of components of the end-members. Maar-diatremes that were formed by repeated discrete explosions but that preserve evidence for a component of subsidence due to magma withdrawal probably formed above shallow, relatively short-lived (decades?) magma reservoirs (sills), often within the context of a monogenetic episode (e.g., Valentine and Krogh, 2006). MFCI explosions may have occurred during "leaks" from the shallow sills, sending small, bubble-poor batches of magma upward where they were able to interact with groundwater. Questions that need to be addressed to understand this intermediate case include the mechanisms of formation and magma evolution within shallow sills, and mechanisms and rates of leakage from them.

Other intermediate systems appear to have had longer-lived magma reservoirs, which occasionally leaked small batches of magma that formed end-member type maars. In such cases the magma reservoir itself may act as a filter that promotes conditions for phreatomagmatic explosions above it, as magma ascending from depth in higher-flux batches is mostly trapped in the reservoir. The reservoir in turn mainly produces low-flux "MFCI-able" leaks with occasional high-flux eruptions, noting that the MFCI process for more viscous magmas is likely to be related to contact of water with fractured melt (Austin-Erickson et al., 2008). The maars can form at different locations above the reservoir and their depressions may overlap to form a larger composite depression that also has a subsidence component produced by episodes of sustained, magmatic volatile-driven discharge. If caldera-bounding faults formed during such an event, subsequent low-flux leaks may be focused along the faults, producing the type of phreatomagmatic circum-caldera deposits at Latera caldera, described above. Again, the mechanisms and rates of leakage from the shallow reservoirs is a key problem to address. Products of sustained-discharge eruptions that are inferred to have also had significant magma-water interaction are subject to the same cautions raised above for calderas.

To summarize, maar-diatremes and explosive calderas form a spectrum of explosive volcanic depressions, and we think that much can be learned through a convergence of research on these end-members. Key problems relate to the mechanisms of interaction of water with high-viscosity, bubbly, and in many cases already-fragmented magma ascending at high fluxes, and to the controls on magma leaks from shallow crustal reservoirs, where the leaks provide the "fuel" for phreatomagmatic activity while the reservoir forms a source of subsidence if large volumes are rapidly erupted.

Author Contributions

All four authors contributed to the concepts and perspectives presented in the paper, which developed through long-term collaborative work. DP and GV led the writing of the manuscript.

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