Chapter 13

How Polygenetic are Monogenetic Volcanoes: Case Studies of Some Complex Maar-Diatreme Volcanoes

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Additional information is available at the end of the chapter

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Abstract

The increasing number of field investigations and various controlled benchtop and large-scale experiments have permitted the evaluation of a large number of processes involved in the formation of maar-diatreme volcanoes, the second most common type of small-volume subaerial volcanoes on Earth. A maar-diatreme volcano is recognized by a volcanic crater that is cut into country rocks and surrounded by a low-height ejecta rim composed of pyroclastic deposits of few meters to up to 200 m thick above the syn-eruptive surface level. The craters vary from 0.1 km to up to 5 km wide and vary in depth from a few dozen meters to up to 300 m deep. Their irregular morphology reflects the simple or complex volcanic and cratering processes involved in their formation. The simplicity or complexity of the crater or the entire maar itself is usually observed in the stratigraphy of the surrounding ejecta rings. The latter are composed of sequences of successive alternating and contrastingly bedded phreatomagmatic-derived dilute pyroclastic density currents (PDC) and fallout depositions, with occasional interbedded Strombolian-derived spatter materials or scoria fall units, exemplifying the changes in the eruptive styles during the formation of the volcano. The entire stratigraphic sequence might be preserved as a single eruptive package (small or very thick) in which there is no stratigraphic gap or significant discordance indicative of a potential break during the eruption. A maar with a single eruptive deposit is quantified as monogenetic maar, meaning that it was formed by a single eruptive vent from which only a small and ephemeral magma erupted over a short period of time. The stratigraphy may also display several packages of deposits separated either by contrasting discordance surfaces or paleosoils, which reflect multiple phases or episodes of eruptions within the same maar. Such maars are characterized as complex polycyclic maars if the length of time between the eruptive events is relatively short (days to years). For greater length of time (thousands to millions of years), the complex maar will be quantified as polygenetic. These common depositional breaks interpreted as signs of temporal interruption of the eruptions for various timescales also indicate deep magma system processes; hence magmas of different types might erupt during the formation of both simple and complex maars. The feeding dikes can interact with groundwater and form closely distributed small craters. The latter can coalesce to form a final crater with various shapes depending on the distance between them. This observation indicates the significant role of the magmatic plumbing system on the formation and growth of complex and polygenetic maar-diatreme volcanoes.

Keywords: maar-diatreme, polygenetic, monogenetic volcanism, complex maars, dike injection

1. Introduction

Monogenetic volcanoes represent the most common type of subaerial volcanoes not only on Earth but in the solar system [1–3]. These volcanoes, including maars, tuff rings, tuff cones and scoria cones, and sometimes short lava flows, are generally believed to form by a single short-lived eruption probably during a brief period of time (e.g., hours to days). The eruptions are typically fed by small volume of magma of any type, producing simple and small-volume volcanoes that predominantly clustered in lowland volcanic fields at the footprints of polygenetic volcanoes (e.g., [4–7]). The term polygenetic is often used to refer to volcanoes constructed by multiple eruptive events over a large timespan and characterized by complex volcanic and geochemical evolution such as stratovolcanoes (e.g., [8]). The same applies in this study. Most of the small volcanoes are generally characterized by simple and easy to understand volcanic sequences. However, the reality is different and that is what this book chapter tries to demonstrate. For instance, increasing investigations in several volcanic fields have shown that small volcanoes can exhibit, in special cases, a contrasting stratigraphy consisting of tephra units and other lava flows sometimes of different geochemical compositions (e.g., [8–10]). The eruptive units are sometimes deposited periodically with short or even prolonged inactive periods between eruptive events, indicating an evolution that cannot be explained with a single eruption (e.g., [11–13]). Additionally, such intricate trend of complexity is even more obvious with maar volcanoes that are the results of explosive magma-water interactions (molten-fuel-coolant interaction), a process causing fragmentation of both the magma and country rocks close to the surface (e.g., [14–19]. Their eruptive sequences are, therefore, heavily influenced by the magma internal (physicochemical) attributes as well as the environmental parameters that are largely expressed by the nature of the geologic substrate and the availability of external water to cause explosions. Maars are, therefore, probably the most complex and suitable bunch of small-volume volcanoes where complex sedimentary succession of their rim (and underground) architecture is expected. In this chapter, we intend to explore this diversity through some recent studies and own research. Examples will include recently documented small volcanoes showing complex stratigraphy, compound volcano edifice, and complex eruptive history, in various volcanic fields, including the Western Australian volcanic field (e.g., [10, 20]), the Coli Albani volcanic complex in Italy [13, 21], the Cameroon volcanic line [11, 22, 23], the Eiffel volcanic field [24, 25], the Trans-Mexican Volcanic Belt [26–28], the Central Volcanic Range of Costa Rica [12], the Bakony-Balaton Highland Volcanic Field in Hungary [29–31], as well as Auckland volcanic field in New Zealand [32–34].

This chapter focuses on phreatomagmatic-derived volcanoes, especially maar-diatremes, for which an important number of field investigations and various types of controlled benchtop and large-scale experiments have permitted to constrain processes involved in their formation, such as the mechanism of explosion (e.g., [35–39]), the quantification and control of magma-water interactions during the fragmentation process in regard to the potential maximum energy release that such process can provide (e.g., [35, 40]), the cratering process (e.g., [17–19]), the resulting volcanic facies preserved in a volcanic edifice and depositional processes associated with the distal regions of such volcanoes in the inter-volcano region (e.g., [29, 41–47]), as well as the characterization of the changes in the eruptive styles in the course of their formation (e.g., [48–52]), and the geochemical processes associated with their formation from the melt extraction and deep fractionation prior to eruptions to the processes influencing the rising magma batches (e.g., [8, 21, 52–55]). The reader can therefore refer to [56–58] for detailed review on scoria cones. The main purpose of this chapter is to highlight the main features that could help to understand the formation of complex maars and how we can recognize and discriminate The latter from simple maar volcanoes. Thus, we will emphasize where poly-activity have been identified such as the Purrumbete Maar, Australia (e.g., [20]), Albano Maar, Colli Albani volcano, Italy (e.g., [13, 21]), Hule Maar, Costa Rica (e.g., [12]), or Barombi Mbo Maar, Cameroon [22, 59]. In the light of several previous discussions around the monogenetic volcanoes (e.g., [6, 58, 60]), we present some key similarities and dissimilarities within simple and complex small-volume volcanoes, especially maars, so that a better definition for those volcanic end members could be understood. We also discuss what processes might drive complex activity at maar volcanoes in order to propose a conceptual model that can summarize the origin and growth of this type of end-member volcano.

2. General features of maar-diatreme volcanoes

In many volcanic fields, it is usually common to see a low rim of bedded pyroclastic ejecta surrounding a dried or water-filled depression that cuts into the pre-eruptive ground (**Figure 1**). This structure is usually called maar. Maar is a German-derived word that means "crater lake," whose origin derived from the Latin word *mare* (sea). In 1819, in his book "Die erloschenen Vulkane in der Eifel und am Niederrheine," Johann Steininger was probably the first to coin the term maar to describe a volcanic feature while working in the Eifel volcanic area in Germany, in which the craters are usually occupied by lakes. The term was then widely used by Ollier [61] and Lorenz [62, 63] and others authors cited therein. These early papers put the term of maar into the scientific literature as an important volcanic landform formed through phreatomagmatic eruptions, which is now applied to similar craters (e.g., [12]). A maar stands for a volcanic crater that is cut into country rocks (a few meters or tens of meters above the preexisting ground surface) and surrounded by a low-height ejecta rim composed of pyroclastic deposits of few meters to up to 200 m thick above the syn-eruptive surface level (e.g., [64]). The term maar is sometimes also used only as a morphological term.

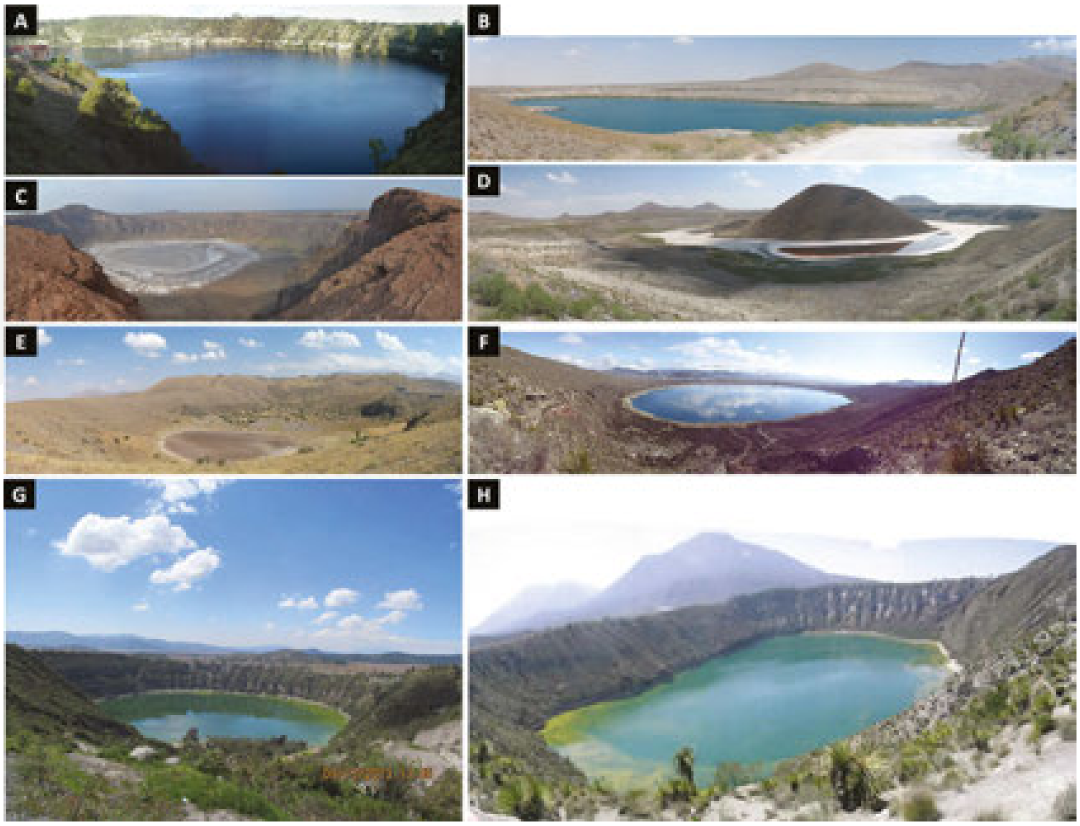

Figure 1. Photos showing the typical landform of some maar volcanoes. (**A**) Blue Lake Maar (Mount Gambier, South Australia), (**B**) Aci Golu Maar (Turkey), (**C**) Al Wahbah Maar (Harrat Khisb in western Saudi Arabia), (**D**) Cora Maar (Central Anatolia), and (**E**) Meke Gölü Maar (Turkey), (**F**) Alchichica Maar, (**G**) Aljojuca Maar, and (**H**) Atexcac Maar of the EMVB, Mexico.

Maar volcanoes are characterized by a relatively small crater size, hundred meters to up to 5 km in diameter [65], with few dozen of meters to up to 300 m deep [9]. The craters are mostly circular in shape, although in some cases an irregular morphology can be observed due to a formation through the injection of discrete dikes at several but closely spaced explosion craters/centers to the main crater (e.g., [55]). Examples of such simple maars are certainly the most widely spread in monogenetic volcanic fields, such as the Eifel volcanic field, western central Germany, where many maars are characterized by small crater diameters ranging from 83 to 1580 m [25] and low tephra deposit thickness, e.g., Ulmener Maar, 7.5 m thick, Pulvermaar, 27 m thick, or Meedelder Maar, 23 m thick[24]. The same feature is observed with some maars of the Trans-Mexican volcanic field (e.g., [66–68]) or those of the Quaternary Auckland Volcanic Field in New Zealand (e.g., [69]), as well as maars of the Sabatini Volcanic District in the Roman Province of Central Italy (e.g., [70]). The crater floor usually lies well below the surrounding ground level and frequently exhibits near-vertical crater wall escarpments (e.g., [6, 8, 71]). On the other hand, the ejecta rings of maars are characterized by sequences of successive alternation and contrastingly bedded pyroclastic deposits. Much of the bedding forms by dilute pyroclastic density currents (PDC), blast and fallout depositions after phreatomagmatic explosions. This produces a range of beds, typically changing from thick, structureless, and commonly block-rich near the vent to well-developed medial cross-bedding and dune-form and thin distal planar beds [12, 34, 42, 72, 73]. In many cases, occasionally interbedded Strombolian-derived spatter material or scoria fall units are observed. This exemplifies the changes in the eruptive styles during the formation of a maar volcano (e.g., [45, 49, 74, 75]). The deposit sequence also commonly contains large amounts of lithic material that is entrained from the country rock basement and in some cases accretionary lapilli that is an indicator of free moisture or water droplets in the moving two- or three-phase current [76–78]. Bedding sags are common sedimentary features and their abundance usually reflects the violent excavation of blocks of country rock or magmatic bombs during the formation of the diatreme and the ballistic nature of eruptions (e.g., [55–57]) (**Figure 2**).

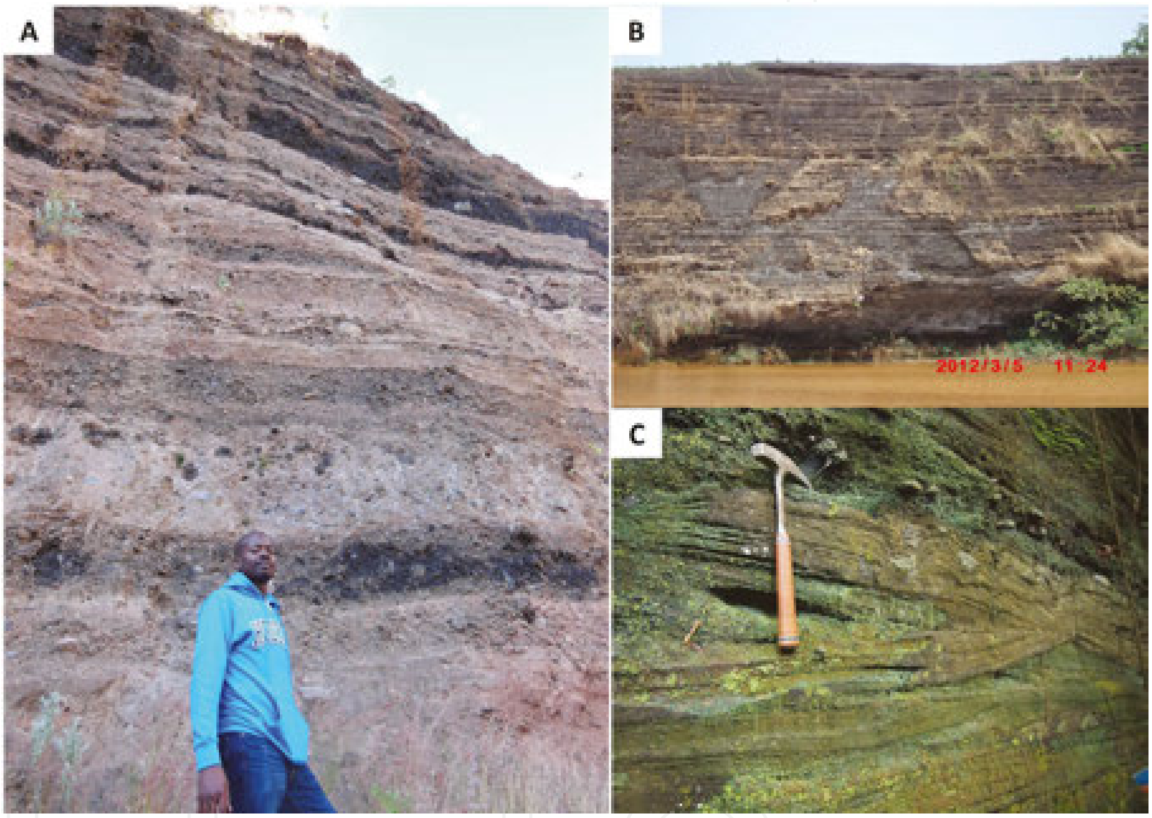

Figure 2. Some features observed on maar deposits. (**A**) Contrasting surge and fall units of the Alberca de Guadalupe maar deposits (Zacapu basin, Michoacán, Mexico); (**B**) thinly stratified surge deposits of Nyos Maar, Cameroon; (**C**) soft structure deformation and impact sags in a sequence of Barombi Mbo Maar deposit, Cameroon.

The estimated volumes of bulk-ejected tephra and the corresponding dense rock equivalent (DRE) using different methods such as isopach and/or juvenile content of the bulk deposits or by applying interpolation techniques on digital elevation models (DEM) along with rock textural data collected from the field (e.g., [69]) are usually very small (≤1 km^3). This suggests that maars are very small-volume volcanoes compared to the middle-size shield volcanoes (1–10 km^3) and the large polygenetic volcanoes (10–10,000 km^3). The latter ones have a stable melt source over prolonged periods, where shallow magma storage systems are expected to develop and form a well-defined and stable vent zone over a long time, producing large volumes of materials and potentially chemically diverse eruptive products [60]. The duration of volcanic activity leading to their formation would therefore be probably short and even reduced to a single eruptive event (e.g., [6]).

Another feature that is usually associated to maars is a diatreme. Because of the occurrence in maar deposits of an important amount of accidental lithic fragments of the country rock, it was inferred that below a maar there is inevitably an extended subsurface inverted cone- or carrot-shaped structure called diatreme (e.g., [29, 79]). Many remnants of well-exposed diatremes have been identified in association with massifs of plutonic rocks of different compositions and also in ore deposits fields, where in the form of brecciated and pebbly pipes, they have frequently served as the most favorable ore- and diamond hosting structures. However, even if geophysical studies have demonstrated the presence of this structure beneath maars (e.g., [80, 81]) and that in rare occasions drill holes have reach the upper level of the diatreme facies of the maar-diatreme volcanoes (e.g., [62, 63]), the opportunity to examine a diatreme and an ejecta ring belonging to the same maar-diatreme volcano is rare, posing some difficulty to establish the direct relationships between the ejecta ring of a maar, the eruption processes, and the growth of its underlying diatreme. Nevertheless, the diatreme beneath maars might consist of deposits formed during eruptions that can be described collectively as "diatreme deposits," including bedded diatreme fill; un-bedded diatreme fill, including in zones that cut across bedded fill; as well as root zone deposits (e.g., [12], **Figure 3**).

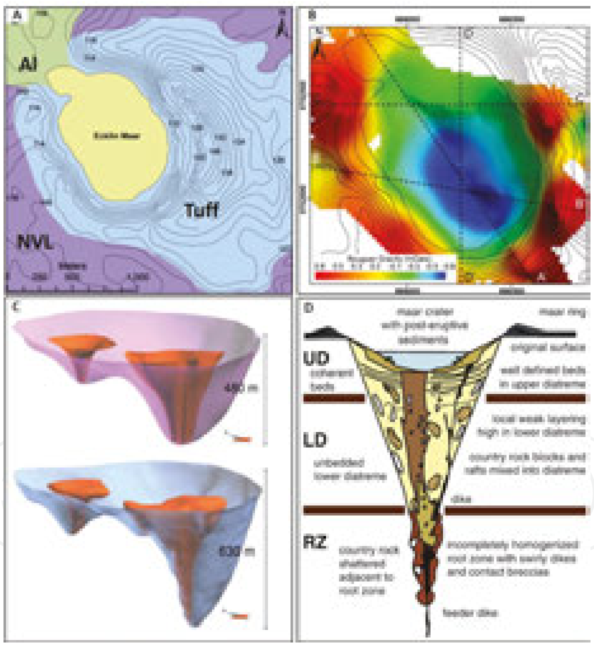

Figure 3. Example of geophysical response from the Ecklin Maar, Newer Volcanics Province, southeastern Australia, (images from Blaikie et al. [81]). (**A**) Simplified geology of the maar; (**B**) Bouguer anomaly with regional trend removed showing gravity low over the crater; (**C**) 3D model viewed from southwest (upper) and optimized geometry (lower) of the Ecklin diatreme. (**D**) Maar and diatreme structure with distinct parts of the diatremes defined by their typical lithofacies and structure (from White and Ross [82]).

These general features commonly characterize a simple maar volcano that is considered as monogenetic volcano sensu stricto. The latter corresponds to a volcano characterized by a single eruptive vent (single crater for maars and tuff rings and unique and regular cone shape for scoria cones) through which only a small and temporal magma supply of single or various compositions erupted once in a brief period of time. This implies that all the pathways of magma supply should have cooled down and ascending routes are no longer favored for the next magma batch (e.g., [60]). In reference to maars or tuff rings, the tephra ring for monogenetic maars would have a relatively regular shape that might follows the morphology of the crater. The stratigraphic sequence is as simple as possible in terms of tephra succession (e.g., no stratigraphic gap or discordance indicative of a potential break in the eruption progression). This simplicity does not only refer to the small thickness or the relatively homogeneous type of deposits (e.g., PDC) that can be observed at some maars, because some monogenetic maars can have complex deposit sequences including dilute PDC, tephra fall and spatter, and sometimes rootless lava flows. The Barombi Koto Maar (Cameroon volcanic line) is an example of this type of maar volcanoes. The deposit sequence of this maar indicates a volcanic evolution comprising an initial phreatomagmatic stage, followed by a late sustained Strombolian activity that formed a small scoria phase, then another phreatomagmatic phase, and a late sustained Strombolian-style explosive eruption that formed a small scoria cone constructing an islet in the middle of the crater lake, without any break in the preserved eruptive sequence [23]. Nyos Maar in Cameroon could also be a good example. Nyos Maar is characterized by a lower lava flow unit (8 m thick) and an upper dilute PDC unit (~70–80 m thick on the eastern lakeshore), indicating an initial fire-fountaining phase [83] and a series of phreatomagmatic explosions [83] without gap between the eruptive sequences indicating a continuous eruption [84].

3. Features of complex maar volcanoes

As discussed above, maar-diatreme volcanoes are commonly composed of a crater, an ejecta ring, and an underlying diatreme structure that is filled by various fragments from the ascending magma and the country rock. In addition, they are characterized by small eruptive volumes that usually result in the simplicity of their volcanic edifice. The small eruptive volume is also interpreted as a result of a short volcanic activity and even reduced to a single eruptive event. However, even characterized by a small eruptive volume, all maar-diatreme volcanoes are dissimilar in terms of volcanic edifice morphology. Like their "cousins" tuff rings and scoria cones, which are usually considered as monogenetic volcanoes, these volcanoes are very complex especially when their stratigraphic sequences, the morphology of their craters and/or their ejecta rings, or the chemical composition throughout the sequence are examined in detail. For instance, Németh et al. [85] and Németh and Kereszturi [60] following earlier definitions of monogenetic volcanoes (e.g., [4]) highlighted different types of small volcanoes that can be encountered in monogenetic volcanic fields. These included monogenetic volcanoes sensu stricto and complex monogenetic volcanoes with multiple eruptive episodes, which in some cases are characterized by a complex magmatic feeding system. In the literature there are numerous examples for such eruptive behavior: Crater Hill [32], the long-lived scoria cone and lava flow complex of Rangitoto Auckland volcanic field, New Zealand [86], and Motukorea tuff ring in Auckland volcanic field, New Zealand [87, 88]; the Kissomlyó in Hungary (e.g., [89]); the Udo, Songaksan, and Yangpory in South Korea (e.g., [8, 54, 90]); the Purrumbete Maar in Australia (e.g., [10]); Fekete-hegy [91], Bondoró [31], and Tihany [29] from the Bakony-Balaton Highland Volcanic Fields in Western Hungary; some maars in the Eifel volcanic field, Germany [92, 93]; the Cerro Negro scoria cone, Nicaragua [94, 95]; and El Volcancillo, Mexico [96]. All of these examples were likely constructed over a longer period of time (from Ky to My). This was inferred from the fact that those volcanoes, even having a small eruptive volume, have a complex stratigraphy and tephra ring architecture suggesting that multiple eruptive episodes contributed to the growth and destruction of the volcanic edifice (e.g., [85]). These volcano categories are revisited hereafter with an emphasis on maar-diatremes.

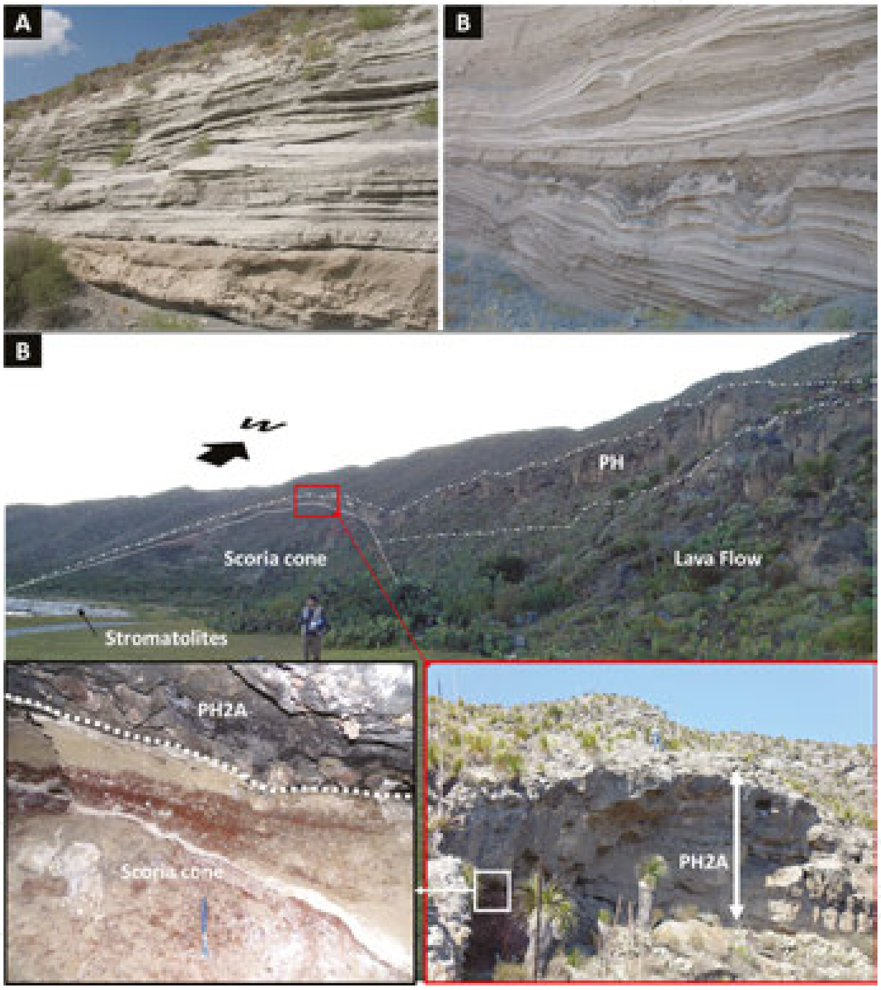

Figure 4. Textural unconformities in the Meke Gölü Maar deposit, Turkey (**A**), and laterally discontinuous thick cross-laminated beds in the Cora Maar deposit (**B**). (**C**) Complex well-marked discordant contacts and truncation surface between the deposit packages at Alchichica Maar, Easter Mexican Volcanic Belt (EMVB). Note the discordant contacts between the scoria cone, the lava flow, and the maar pyroclastic deposit sequence (PH). The left lower photo shows a sharp contact between the scoria cone and the pyroclastic level PH.

As with polygenetic volcanoes, multiple eruptive events have the capability to produce with time a large cumulative volume of tephra and/or lava products around a single or multiple volcanic vents. In the case of small volcanoes, this probably will result in the deposition of thick eruptive sequences. However, the volume or the thickness of deposits might not be a common feature to all small volcanoes where multiple eruptions or polycyclic activity is observed. This is mainly because these parameters depend directly on the volume of magma involved in each eruptive cycle and, in the cases of maars and tuff rings, to the depths at which explosions took place to excavate an important fraction of country rocks that compose up to 90% of ejected materials (e.g., [12]). Nevertheless, the consequence of the poly-activity within small volcanoes is the construction of complex stratigraphic sequences. These complex volcanoes usually display packages or depositional units made of erupted materials that in some cases can be directly apparent on the field by deposit textural differences, chaotic deposits separated by a lava flow horizon (e.g., [97]), and/or a dike cutting through the deposit units (e.g., [98]). Textural differences in pyroclastic sequences can also show altered or palagonized juvenile-rich deposits that underlie a fresh surge or fall unit within the same eruptive sequence (e.g., [33, 97, 99]) or the presence of centimeter- to decimeter-thick light brown to yellowish pedogenized ash horizons in some deposits [21]. Well-marked structural discordant contacts or truncation surface or erosional limits between the deposit packages (e.g., [26, 34, 66, 76, 92, 100]) are some of the main features observed within the stratigraphic sequence. These are characterized by high-angle, laterally discontinuous or thick cross-laminated levels and angular unconformities between pyroclastic deposits, ranging in outcrop scale from centimeter to decameter long (**Figure 4**). In many other cases, one of the features that separate the eruptive packages is a paleosoil (e.g., [12, 22, 42, 101, 102]).

Because the formation of a soil requires a minimum time ranging from hundreds to millions of years depending on the climatic conditions (e.g., [103]), this feature highlights how long was the period of the eruptive activity and is therefore commonly used to distinguish between simple monogenetic and complex polygenetic small volcanoes. However, multiple eruptive events might occur within a short timescale without the formation of paleosoils between eruptive packages, and the surrounding deposits can display the same stratigraphic and structural complexity [9]. Note that in historic times only a few maar-diatreme volcanoes erupted. In 1954 the Nilahue Maar erupted in Chile during almost half a year, but the main eruptive phase ended after 10 days producing a maar crater of 300 m in diameter. In contrast, in 1977 the Ukinrek West Maar erupted only for 3 days and generated 10 m-thick tephra ring, a 170 m wide (rim to rim) and 30 m deep maar crater (e.g., [100, 104]). This information is certainly not enough to generalize about the duration of a sequence of maar-forming eruption, making it difficult to easily distinguish between the complex maars. Fisher et al. [105] suggested that an eruptive pulse is a single explosion or detonation that may last a few seconds to minutes producing an eruption column from which particles will sediment to form a single well-defined tephra bed. On the other hand, an eruptive phase consists of series of strong explosions that can last a few hours to days generating pulsating eruptions columns and formation of several well-defined beds. Depending on the style of magma fragmentation, an eruptive phase may alternate between explosive and effusive eruptive phases [106]. It is also important to note that the eruption here is fed by a single magma batch or multiple magma batches that could be of the same or different compositions (e.g., [60]). The eruptive episode or single eruption is composed of several eruptive phases, which may last a few days to months and in some volcanoes for years [105 ,106].

Following these definitions, (1) a complex monogenetic volcano can be categorized as the one where multiple eruptive phases have been identified. This implies that magma batch or batches feeding the system erupted almost at the same time, with a very short break (days to years [9]) insufficient to allow any significant erosion or alteration (palagonization) at the top of each eruptive package (deposits of one eruptive phase) and especially the formation of a paleosoil. This type can experience vertical and lateral vent migration and dike arrests which are very common processes in the formation of maar-diatreme volcanoes (e.g., [28, 107, 108]).

In contrast, (2) complex monogenetic volcanoes with polygenetic inheritance are those in which at least two eruptive episodes have been identified, i.e., where a paleosoil or any indication for time gap from the eruptive sequence can be established (time obtained by conventional dating methods) that separates two sequences of deposits, each composed of multiple packages (e.g., [22, 101]). This also implies that the time gap between the eruptive episodes is significant, several thousands of years as observed with the Albano Maar (e.g., [13, 21]), the Barombi Mbo Maar (e.g., [59]), the Bondoró Volcanic Complex [31], the Hule Maar (e.g., [12]), or Ilchulbong tuff cone [9].

While the erosional limits or the presence of paleosoils within the stratigraphic sequence would mainly indicate a time gap between eruptive cycles, structural truncation surfaces or discordant contacts usually result in complex tephra ring architectures, especially when deposit packages have different dipping angles (e.g., [9, 20]). This suggests an influence of the variation in the eruptive vents or some tectonic activity with the progression of eruptions that have been attributed to the formation of complex craters morphologies (e.g., [17, 20, 26, 27, 90, 91]). Experimental studies have even demonstrated that the size and shape of maar craters might vary depending on the positions and numbers of the explosion loci during their formation (e.g., [109–112]). For instance, according to [111], final crater shapes tend to be roughly circular if subsurface explosion epicenters occur within each other's footprints (i.e., the plan view area of reference crater produced by a single explosion) and elongate if an epicenter lies somewhat beyond the footprint of the previous explosion, such that their footprints overlap. But if epicenters are too far apart, the footprints do not overlap and separate craters result (e.g., [29, 113]). This is likely the process that occurred at the Tihany volcanic complex in Western Hungary, where successive eruptions created three separated volcanic centers (e.g., [29]). **Figure 5** shows this complexity of the crater shape for some maar volcanoes of both monogenetic (e.g., Atexcac; **Figure 5c**) and polygenetic natures (e.g., Albano and Purrumbete Maars; **Figure 5B** and **D**). These maars are characterized by many small craters a minimum of three for the Purrumbete Maar to up to nine for the Atexcac maar [27] that coalesced to form relatively regular or irregular crater morphologies. Many other maars with such complex eruptive evolution and crater morphology have been identified in different volcanic fields. Crater Hill in Auckland Volcanic Field, New Zealand, is characterized by a nearly circular tuff ring of 900–1100 m wide and only 9–15 m thick, surrounding an elliptic irregular crater [115]. The crater resulted from the coalescence of at least four vents spaced along a NNE trending, 600 m-long fissure [115]. Tecuitlapa Maar located in the eastern Central Volcanic Belt of Mexico [28] is characterized by a 1 km-diameter irregular crater which is an alignment of scoria cones. It is thought that activity there began in the eastern part of the crater with phreatomagmatic

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eruption, where basaltic magma interacted with liquefied tuffaceous sediments. Then, the explosion locus gradually moved westward producing an elliptical crater. The eruptions then dried out and began to produce scoria/spatter cones with nested craters along the same alignment parallel to regional structural trends [28]. Chako Tchamabé et al. [11] demonstrated also that similar migration of explosion vent occurred at the polygenetic Barombi Mbo Maar, forming a very large, amalgamated maar crater with a total diameter of 2.5 km. A minimum of three and a maximum of five craters were suggested according to the three eruptive episodes identified and the potential implication of several dike injections within the progression of activity [55].

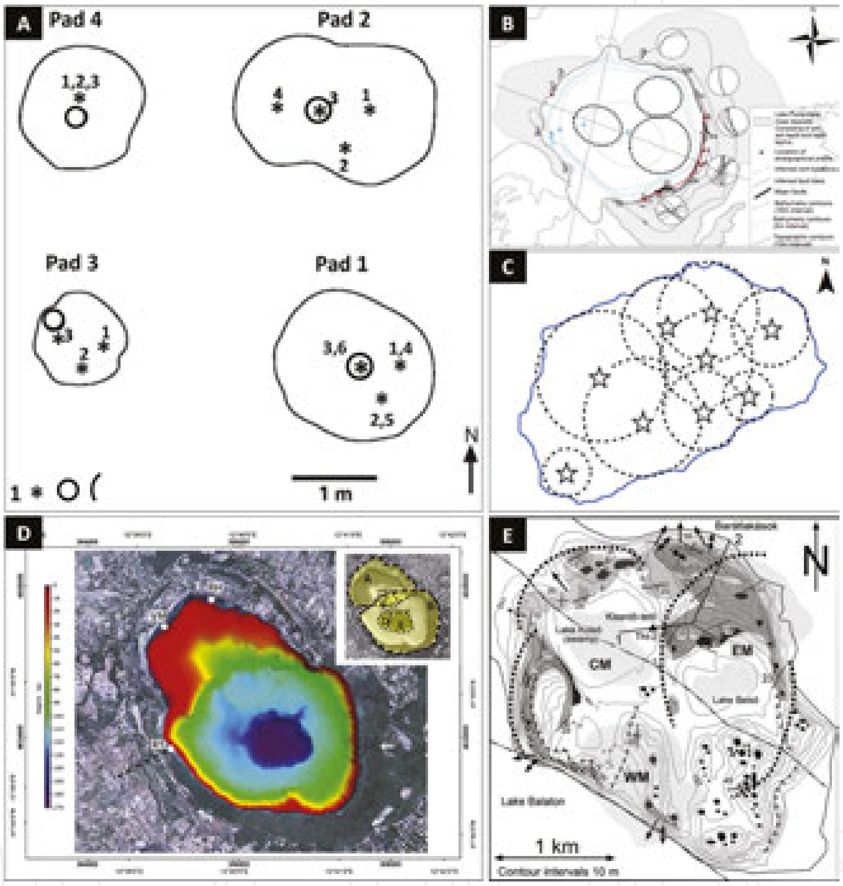

Figure 5. Complexity of crater morphology of maars. (**A**) Shapes of final crater rims resulting from experimental study showing the effect of vertical (Pad 4), lateral (Pads 2 and 3), and both (Pad 1) series of explosions (after Valentine et al. [111]). Bold circle, low point in each crater; 1, 2…, numbers of blast epicenters (asterisk). (**B**, **C** and **D**) Crater shapes and inferred number of vents (dash circles) for Purrumbete Maar (after Jordan et al. [20]), Atexcac Maar (after López-Rojas and Carrasco-Núñez [27]), and Albano Maar (after Anzidei et al. [114]) respectively. (**E**) Complex Tihany volcanic center where large distances between explosion vents have formed three distinct craters (after Németh et al. [29]).

Complex crater morphology (e.g., size and shape) could thus be considered as other useful features that characterize complex maars. However, distinguishing between simple maars and complex ones based on the morphology of the crater alone might be confusing. As noted earlier, simple monogenetic maars can present both regular (subcircular to circular) and irregular crater shapes, irrespective to their sizes. This is probably because multiple batches of magma might cause explosions simultaneously at several locations near the main center of the crater (e.g., [37, 103]), resulting to the formation of an irregular crater-shaped and a complex but simple deposit sequence in which discordances are scarce. Sill complexes are present in some monogenetic volcanic fields and suggested to fed some maar-diatreme-forming eruptions (e.g., [18, 34, 116–119]). In addition, investigations have shown that the crater morphology and even the architecture of pyroclastic deposits and evolution of maar-diatreme volcanoes can be highly affected by the type of environment—hard substrate (rocks) or a soft substrate (unconsolidated volcaniclastic or sedimentary deposits)—in which they are emplaced (e.g., [82, 91, 120, 121]). In soft substrates, maar-diatreme volcanoes tend to have large and bowl-shaped craters, with gently dipping inner walls [91]. Recent analog experiments as well as field observations from classical diatremes cut into "soft substrate" showed that the diatreme wall can be steep for such maars that cut through soft substrate (e.g., [121–125]). This might be valid for the geometry of the upper part of the maar-diatreme volcano, especially for its crater, given that the number of individual eruptions can also heavily affect the final crater-diatreme morphology, and as many explosive events take place hence as large and old as your maar, the role of the substrate physical conditions will be reduced (e.g., [125]). In contrast, maars formed in hard-rock environment tend to be irregular, small in size and characterized by funnel-shaped and vertical (e.g., Joya Honda, Mexico [126], Nyos Maar, Cameroon [127]) to steeply dipping crater walls. For instance, in the Calatrava volcanic field in Spain, [120] measured and compared the crater sizes and shapes of 60 maars formed in hard substrate and 66 maars formed in soft-substrate basin-filling sediments. While the average crater radius of maars in hard substrate setting is $\sim$ 339 m, those in the other setting have an average of 556 m, indicating that in this volcanic field, the size of the craters for soft-substrate maars is 64% larger on average than that of hard-substrate maars, though the average crater shape in aerial view is quite similar [121]. Maar crater shapes can also be strongly controlled by the presence of any pre-volcanic lithological situations, including older cones that might have been dissected by the maar-forming eruption, or when explosions occur in a preexisting crater form by previous activity (e.g., [128]). The initial shape of the crater might even change with time due to erosion and slumping of the walls and tephra ring (e.g., [18, 79, 129–131]), shallowing the crater slope and reducing the relief. Older maar basins, for example, could have strong erosion modification along their margins and also could be filled with post-eruptive debris, enlarging the original size of the crater. Unusually large maar lake with irregular boundary might certainly results from complex and migrating explosion locus in the area of the crater floor resulting in complex collapse event and scalloped crater wall architecture. Therefore, it is possible to wrongly interpret a maar with complex crater outline as complex maar as its erosion progresses. Large and complex crater outlines can equally mean either a complex eruptive history or long-lasting erosion history; then one has to check the eruptive sequence carefully not only the morphology of the crater. Correlations should be done between the sequence of activity, the different eruptive packages to the number of craters/vents, and probably the distance between them before using the crater morphology to characterize complex maars, as the crater morphology reflects the complexity on the growth of the volcano (**Table 1**).

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Maars	Stratigraphy				Crater morphology				Genetic nature
	Thickness (m) of deposit rim (maximum section)	Number of eruptive units	Transition style between deposit packages	Geochemical composition of erupted materials	Size (km)	Number of vents or potential crater basins and relative distance between them	shape	Depth (m – under lake surface)	
BMM	126	3	Paleosoils	Bimodal	2.5	~5 small craters closely distributed	Subcircular	110	Polygenetic
Tecuitlapa	50–70	4	Facies transition	–	1.3 × 1	Undetermined but at least six cinder vents have been highlighted [28]. The positions of the explosion locus are unknown but are distributed laterally following a structural fault	Elliptical	–	Monogenetic
Purrumbete	40	4	Three major Structural discordances	Bimodal (polymagmatic)	3	Three craters closely distributed [10]	Subcircular	45	Polycyclic
Albano		3	Paleosoils	Complex		Five craters closely distributed	Elliptical		Polygenetic
Hule		3	Paleosoils and facies transition	Bimodal [12]	2.3 × 1.8	Three lakes separated by two intra-maar pyroclastic cones and lava flows [12]. Assuming	Sub circular for the whole basin,	Vary for each of the three lakes (Hule, 26.5; Congo, 14.6;	Polygenetic

Maars	**Stratigraphy**				**Crater morphology**				**Genetic nature**
	Thickness (m) of deposit rim (maximum section)	**Number of eruptive units**	**Transition style between deposit packages**	**Geochemical composition of erupted materials**	**Size (km)**	**Number of vents or potential crater basins and relative distance between them**	**shape**	**Depth (m – under lake surface)**	
						the lakes are lying in resulting craters, we may have three small craters among which the main Hule lake shows two vents for [116] located ~500 m from a basin to another (see **Figure 2** in [117])	elongated for the main Hule lake	unnamed, 4 m) [12]	
Atex cac	61	4	Facies transition	–	1.15 × 0.85	Nine potential craters randomly distributed [27]	Elliptical	120	Polycyclic
Crater Hill	9–15	7	Truncation surface and facies transition	Compositional variation due to clino pyroxene ± spinel fractionation	0.656	4 Aligned along a fissure	Elliptical	100–120	Polycyclic

Table 1. Some characteristics of complex maar volcanoes formed from multiple eruptive events. The number of eruptive units is based here on the number and style of transitions identified and in some case corresponds to the number of eruptive events.

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4. Growth of complex monogenetic volcanoes

The eruptive mechanism associated with the formation and growth of monogenetic volcanoes is neither well known nor uniform actually and is somehow attributed to a wide range of magmatic and magma-water interaction-driven explosions at both shallow and deep levels vertically and laterally within the substrate [22, 23, 34, 88, 98, 99, 132, 133]. However, the eruptive timespan for the development of complex monogenetic volcanoes makes a big difference compared to the monogenetic sensu stricto end members. The time in this context is certainly related the timescale of magmatic process in the mantle beneath the volcano. In fact, it is much longer and it is sometimes comparable with large polygenetic volcanoes that are characterized by subsequent production of significant volumes of magma with time. Recent studies have shown that at monogenetic volcanoes, small volumes of melt can segregate from the mantle and readily ascend to the surface through dike or crack propagations (e.g., [8, 54, 55, 134–137]). The segregated melts can rise and erupt simultaneously. In such cases, a polymagmatic monogenetic volcano would form, assuming that the magma batches are of different chemical compositions, such as the Udo volcano in Korea (e.g., [8]). On the other hand, the melts can form with time (e.g., yrs to My), rise, and erupt sporadically. In this latter case, successive vents can be constructed and, depending on the distance between the feeder conduits in the system, can produce the nested or separated vents that characterize these relatively complex volcanoes (**Figure 5**). This process can occur in a typical intra-plate volcanic field such as Saudi Arabia [138] or at basaltic-andesitic polygenetic volcanoes such as Tongariro volcano in New Zealand [139] or at complex maars such as Albano Maar (e.g., [21]) or Barombi Mbo Maar [55] and is broadly accompanied by polymagmatic activity. At Tongariro volcanic Complex in New Zealand, for example, diverse lava flows and pyroclastic units with contrasting chemical and isotopic composition were deposited in a period of 275 Ky, constructing 17 small (>0.3 km^3) to large (>12 km^3) nested and overlapping volcanic cones in a non-systematic orderly progression in space for cone-building events and without any systematic distribution of the vents as well [139]. Freda et al. [21] demonstrated based on $^{40}Ar/^{39}Ar$ ages dating that volcanic activity at Albano Maar (Italy) was strongly discontinuous in time, with a first eruptive cycle at 69±1 ka producing at least two eruptive phases and a second cycle with two peaks at 39±1 and 36±1 ka producing at least four eruptive phases. All these cycles occurred in a narrow surface area centered from each other within only hundreds of meters away, forming a compound volcanic edifice. Using geochemical constraints, they also could demonstrate that each eruptive phase was fed by magmas with different compositions. The complexity in chemical composition was attributed either to the arrival of a new batch of magma during the different eruptive cycles, or to the feeding of the system by the same magma that continuously differentiated and erupted during the whole life of the activity. The eruptive activity at Barombi Mbo Maar in Cameroon follows also such complex volcanic and petrogenetic evolution [55]. In this case, three distinct eruptive events occurred subsequently at 0.5 Ma, 0.2 Ma, and 0.08 Ma [59], fed by magmas with different compositions (**Figure 6**). Petrogenetic constrains there also highlighted the segregation and rise of distinct magma batches with time. During the first eruptive event at Barombi Mbo, successive magma batches of same composition created a first crater, and after a significant reposed period of about 0.3 My, other magma batches some with the same composition with the former one and other with distinct composition were involved. This indicates that during this second eruptive episode, at least two dikes contributed to the formation of another crater close to the first one. The same process occurred during the third episode after another repose period of about 0.1 My.

It can be observed that the production of magmas within these volcanoes is distributed in a longer timescale, covering a 500 ka range for the Barombi Mbo Maar, less than 300 ka at Tongariro, and only 30 ka at Albano Maar. These observations suggest that one of the main factors that might favor polygenetic activity at monogenetic volcanoes is certainly the time necessary for the segregation of small volumes of melt, mantle fertility, available melt, melting and discharge rates, and the quick potential of magma batches to rise to the surface through regional tectonic setting and stress distribution in the crust. It is important to note that beneath such polygenetic volcanoes, there could be several pockets of melting in the mantle.

Because the degree of partial melting may also vary in each pocket of melting depending on various factors (e.g., the P-T condition, mineral phases present and volume of volatile phases in the mantle zone, or the geotectonic context where the volcano is located), the melts can segregate simultaneously or individually in the different melting spots in the mantle and erupt with time. Still, it is not excluded that the same melting point can produce, with time, small but sufficient volumes of melt that can erupt at different locations near the previous vents due to the tectonic control in the volcanic area or following cracks produced during precedent eruptions. This also allows us to suggest that, if beneath a monogenetic volcanic field, there are conditions that can favor in a local mantle zone the existence of multiple melting spots; the melts might raise with time as they are produced to develop complex small volcanoes with multiple eruptions. If the rising magma batches encountered a wet zone near the surface, a complex maar-diatreme will develop (**Figure 6**).

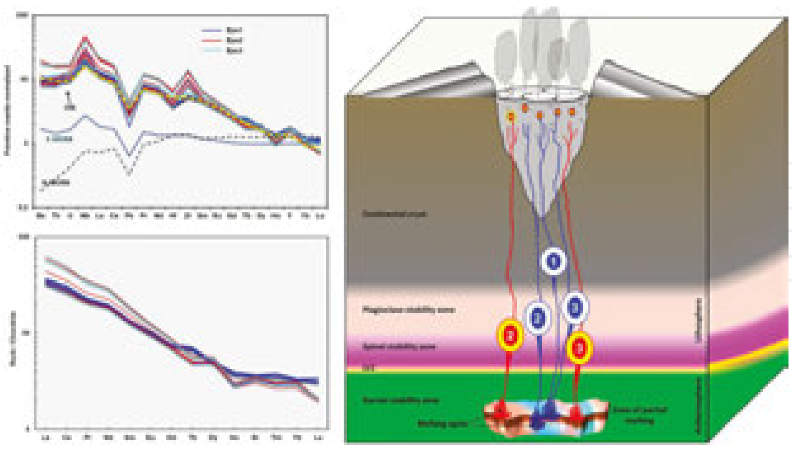

Figure 6. Example of complex compositional variation highlighting complex evolution at Barombi Mbo Maar in Cameroon. The schematic diagram (not to scale) presents the expected feeding system beneath the BMM complex. (1), (2), and (3) correspond to different magma batches feeding the system during the 1st, 2nd, and 3rd eruptive events, respectively, after Chako Tchamabé et al. [59]. The blue and red colors are used here to highlight the different magmas and not the melting loci. Note the involvement of at least two distinct dikes during the second and the third eruptive episodes (details in Chako Tchamabé [55]).

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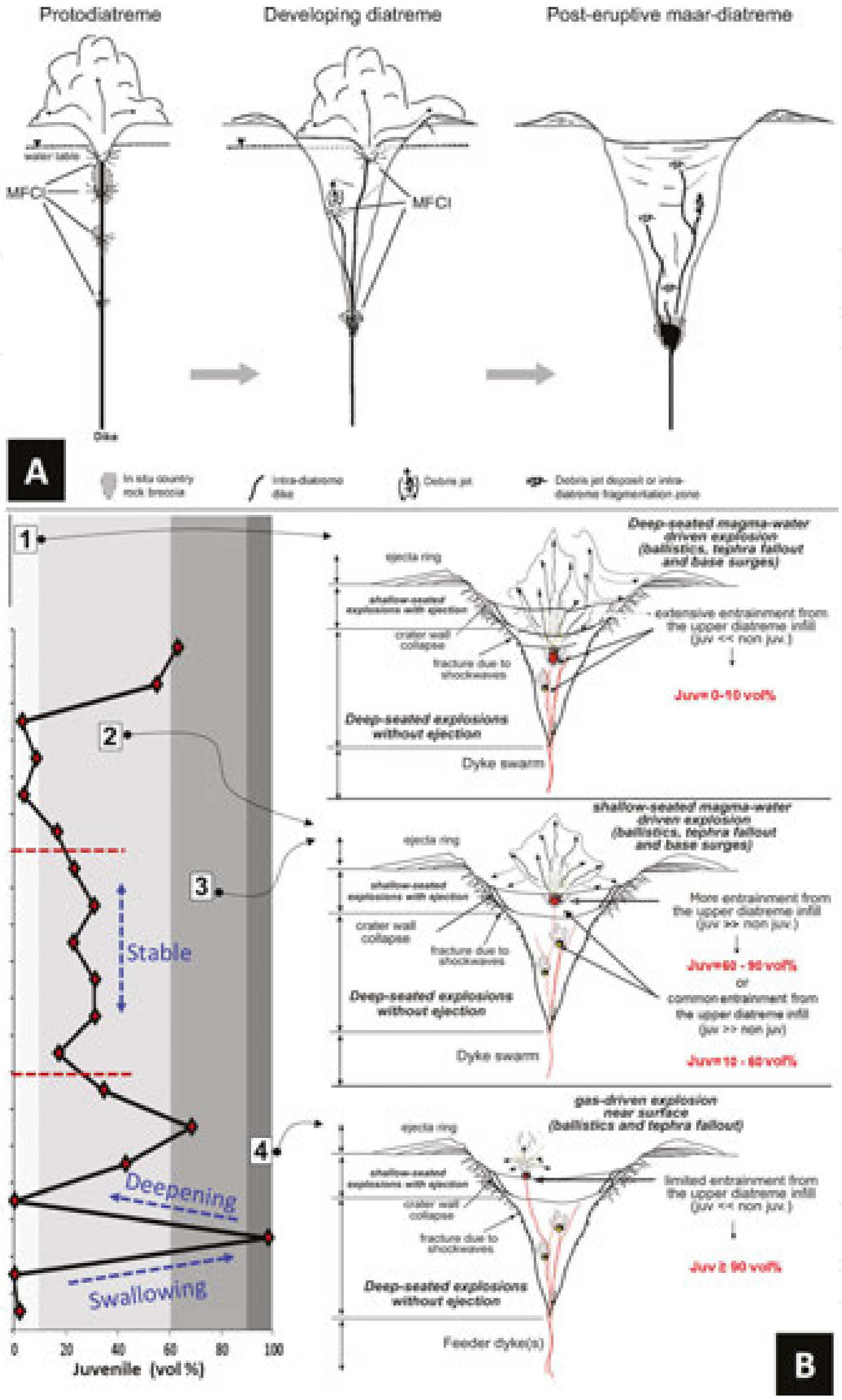

Figure 7. (**A**) Conceptual model after Valentine and White [148] showing explosive molten-fuel-coolant interactions (MFCI) that might take place over a range of depths, brecciating country rock where the explosions take place, but being most effective at shallow depths. (**B**) Comparative schematic model for interpreting the evolution and potential explosion sites (shallow or deep) at maars based on stratigraphic distribution of juvenile components in the BMM ejecta ring. From left to right we have the variation of juvenile populations with a delimitation of domains of juvenile proportion that might reflect a potential model of explosions during maar-diatreme formation. Dashed red lines represent the volcanic hiatus (paleosoils in the deposit) separating the different episodes. The different domains: 1 (juvenile ≤ 10 vol.%), 2 (juvenile = 10–60 vol.%), 3 (juvenile = 60–90 vol.%), and 4 (juvenile ≥ 90) are described in the text and more details in Chako Tchamabé et al. [11].

In the context of growth of such complex monogenetic volcanoes, these observations have an important consequence. The classical growth model of maar-diatremes has long been interpreted following the conceptual model of Lorenz [8], who suggested that the locus of subsurface phreatomagmatic explosions propagates downward with the deepening of a groundwater drawdown cone, as water is used and ejected by explosions [8]. This model implies that the diatremes widen due to slumping and subsidence of host material as their explosion loci deepen [140, 141]. As a result, near-surface occurring lithics would dominate the base of the ejecta rings, while lithics originating from deep-seated explosions location will be deposited on the upper parts of the ejecta ring. Many authors, however, have interpreted the variations in grain size and component distributions in tephra deposits of maars to reflect variations in the intensity of fragmentation during the phreatomagmatic explosions and/or intervening magmatic volatile-driven phases (e.g., [11, 20, 74, 142]) which in turn are often inferred to be related to magma-water ratios (e.g., [143]). It has thus been observed that some maars record intermediate and/or closing phases of magmatic volatile-driven activity in the form of lavas and/or scoria accumulations (e.g., Barombi Koto Maar [23], Tecuitlapa Maar [28]) which are interpreted to result from the absence of groundwater according to [8]. But, the presence of magmatic fragmentation with the evolution of a maar may certainly indicate shallow explosions (e.g., [74]). For instance, Valentine and White [29] propose an alternative model that allows multiple levels of country rock disruption and fragmentation, based on effective mixing by debris jets, an important subsurface transport phenomenon in phreatomagmatic vent complexes that is defined as an upward-moving stream of volcaniclastic debris, magmatic gases, and water vapor ± liquid water droplets, occurring on multiple vertical levels within a growing subsurface diatreme (e.g., [144]). This conceptual model is in accordance with the observed irregular distribution of accidental lithics in ejecta rings (e.g., [145]), field examples on diatreme geometry (e.g., [79]), but also on experimental cratering studies (e.g., [109, 124, 146]) and geophysical modeling (e.g., [80, 81, 147]). Chako Tchamabé et al. [11] also suggested that the variation of juvenile populations within the stratigraphic sequence of maars might reflect a potential mode of explosions during maar-diatreme formation (**Figure 7**). They proposed four domains varying from 0 to 100 vol.% of juvenile contain with the corresponding mode of explosion. For example, a juvenile content of ≤10 vol.% (domain 1) might suggest deep-seated explosions with limited ejection of juveniles and extensive entrainment of fragmented lithics. For 10–60 vol.% juvenile contents, deep- and shallow-seated explosions might occur, with a common entrainment of juveniles and more fragmented lithics, whereas juvenile contents of 60–90 vol.% would suggest shallow-seated explosions with more ejection of juvenile and limited entrainment of fragmented lithics. Up to 90 vol.% of juvenile indicates very shallow (near-surface) gas-driven explosions with ejection of more juveniles. This observation, supported by the conceptual model of [148] for the growth of maars and their diatremes (**Figure 7**), makes clear that explosions may occur at multiple levels, laterally and vertically, contributing to fragmentation and mixing of debris through a combination of upward-directed jets and downward subsidence (e.g., [109, 110, 124, 128, 149]).

However, while those models allow for understanding the diverse eruption scenarios within the formation of simple maars, it might be difficult to determine the growth of complex monogenetic volcanoes, especially complex maars that formed from multiple eruption

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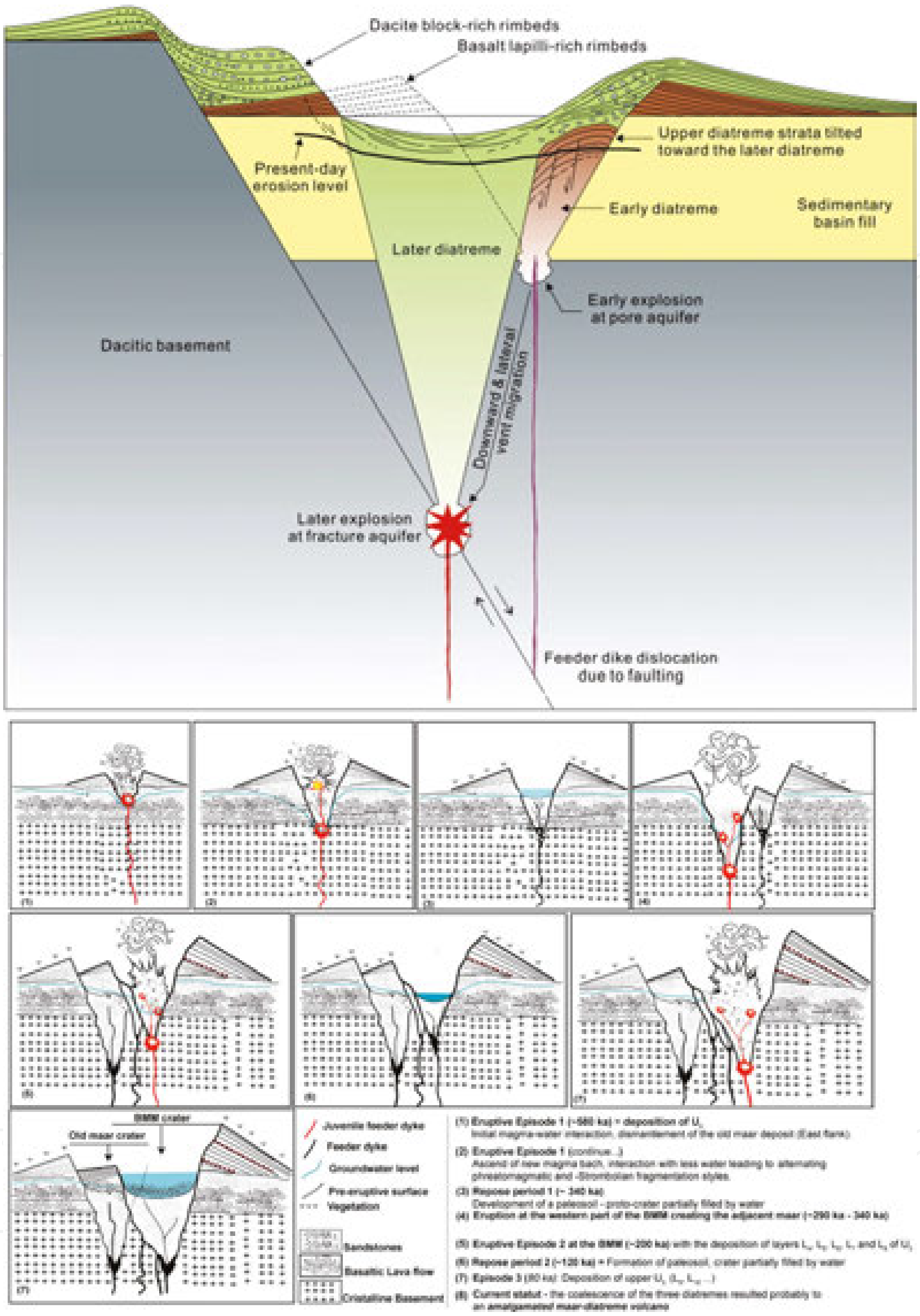

Figure 8. Schematic illustration of the cross-sectional geometry of the Yangpori diatreme (Son et al. [90]) consisting of two cross-cutting diatreme structures, which resulted from migration of the explosion locus associated with basin-margin fault movement (left). Sketch of the temporal evolution and growth of the BMM and its diatreme; here, the explosions started at shallow depth. Afterward, a vertical shift of explosion locus in the substrate followed, producing a scoria-rich layer through alternating phreatomagmatic- and Strombolian-type explosions. Explosions started again after a quiescent period of ~0.3 Ma and magma-water interactions occurring at deeper and at various lateral positions within the diatreme. These explosions widened the crater and deposited more tephra onto the ejecta ring. The explosion pattern may have been the same during the third eruptive episode, continuing to widen the crater and the diatreme (details in Chako Tchamabé et al. [11]).

episodes. Such volcanoes can have dramatic change in the eruption processes given to the overlapping nature of the eruptive products. These can also create truncation and bias in the sedimentary and stratigraphic record as a response of lateral and vertical variation of subsurface explosive loci. The formation of the Yangpori diatreme (South Korea), for example, occurred in two distinct eruption phases, punctuated by sudden lowering of the explosion locus [90]. The first phase of eruption was initiated and maintained at a relatively shallow level within the water-logged basin fills, whereas the second eruptive phase was generated by explosions within a fracture-controlled or joint aquifer within the dacitic basement. This generated two cross-cutting diatreme structures, which resulted from migration of the explosion locus associated with basin-margin fault movement (**Figure 8**). Similar processes were suggested for the Barombi Mbo Maar in Cameroon, but in contrast to the Yangpori diatreme where a tectonically controlled migration was highlighted, new diatremes grew close to the first one at Barombi Mbo due to the discrete injection of new dikes. This implies that the growth process of these complex volcanoes cannot be "predicted" using such growth models, because they are way too complicated in terms of eruptive evolution. A generalized model may not apply for these volcanoes. Each complex monogenetic or polygenetic small volcano should be treated independently, and the growth model for its formation should be done taking into consideration the number of vents identified, the discontinuities observed within the stratigraphy, the eruptive timespan, and probably the geochemistry of the erupted materials.

5. Conclusions

1. Maar-diatreme volcanoes are small volcanic landforms formed as a result of strong MFCI explosive eruptions and usually following a single evolution with a succession of eruptive phases all related to a single eruption, that is closely related in time, and therefore they are usually considered as simple monogenetic volcanoes. However, recent examples of maar volcanoes show a more complex evolution, involving important timescale and breaks in the eruptive activity, changes in the eruptive style, and variations in the magma composition, suggesting the injection of different magma batches during long periods of time. Such complex volcanoes can be grouped into two end members:

   - Complex monogenetic volcanoes that are characterized by multiple eruptive phases but which evolved in a single eruptive episode. Here magma batches feeding the system erupt almost at the same time, with a very short break (months to years) insufficient to allow any significant erosion or alteration (e.g., palagonization) at the top of each eruptive package (deposits of one eruptive phase) and especially the formation of a paleosoil. These are polycyclic monogenetic volcanoes.

   - If the volcano formed during a very large timescale (e.g., Ky to My) and if at least two eruptive episodes are identified with significant time gaps that can be measured by radiogenic dating methods, the volcano surely is a polygenetic volcano. In such cases, paleosoil layers or highly eroded or altered surfaces may separate the eruptive units.

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It is also important to note that for such polygenetic volcanoes, all the eruptions should take place in very close vents that will form a final compound volcanic edifice with overlapping deposits. If the vents are distant ones from others, distinct, but very closely distributed monogenetic volcanic edifices might form.

2. Maars are characterized by composite stratigraphic sequences that are dominated by PDCs and minor fall beds and in some case spatter lava flows. However, for complex maars, sedimentological evidences to establish time gap during the growth of the edifice are crucial to establish the polygenetic nature of the volcano. Maars are also characterized by complex craters morphologies that reflect the complex eruptive evolution and the influence of numerous other factors such as the geologic and tectonic settings, the presence of any pre-volcanic lithological situations including older cones that might have been dissected by the maar-forming eruption or preexisting crater. Because the complexity of the crater morphology applies for both simple and complex maars, observed crater margin needs to be evaluated in respect to establish if the size and shape of the crater reflect the structural boundary of the maar or if this results from an erosion enlarged and/or lake overfilled boundary. In both cases, however, the structural boundary of the maar crater commonly results from the complex explosive excavation history, which is linked to multiple concomitant or timely spaced dike injections, and vent migration in the crater floor that can either be randomly distributed or followed by some structural element such as fissures.

3. The magmatic plumbing system also plays an important role on the growth of complex monogenetic volcanoes, especially maar volcanoes in which diatremes are present. Geochemical variations are sometimes noted at many simple and complex volcanoes. This either means that multiple but near-simultaneous magma batch rise took place or the chemical variations reflect magmatic differentiation en route or both. Thus, if no time gap can be established between the eruptive units, a polymagmatic monogenetic volcano will develop. In contrast, if the complex magmatic activity is correlated with many eruptive episodes, the volcano will be presented as a complex polymagmatic monogenetic volcano with polygenetic inheritance.

4. Though a significant number of large and complex maar volcanoes are known, many of them might really be a reflection of short-lived volcanic events taking place nearly in the same place over longer time (ka range). This chapter clearly demonstrates the detailed complexity of maar eruptions that also emerged from other recent studies on other small-volume volcanoes. Even if the low levels of magmatic differentiation within some of these volcanoes do not allow observation of contrasting magmas in any single volcanic construct, systematic stratigraphically constrained analysis of sample sets might bring significant information on the formation and growth of maars. A complex combination of controlled factors includes the nature of the magmatic plumbing system, the substrate and the influence of local tectonic settings, the melting and ascent rates, groundwater availability, and the multiple injections of magmas successively or, concomitantly during a single eruption, vent migration and establishment of multiple sequential or even possibly concurrent eruption sites. Such detailed investigation would be necessary to

understand each volcanic system and it is only at the end that the volcano may be declare monogenetic or polygenetic.

5. These complex monogenetic volcanoes occur more often than it was previously thought, which is perhaps the reflection of the source region complexity and ascent mechanism. This line of research should be systematically examined in the future because it might hold important clue to understand the geological evolution and volcanic hazard associated with these small-volume magmatic systems located usually far from tectonic boundaries.

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