Title: **Trends in maar crater size and shape using the global Maar Volcano Location and Shape (MaarVLS) database**

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Abstract

A maar crater is the top of a much larger subsurface diatreme structure produced by phreatomagmatic explosions and the size and shape of the crater reflects the growth history of that structure during an eruption. Recent experimental and geophysical research has shown that crater complexity can reflect subsurface complexity. Morphometry provides a means of characterizing a global population of maar craters in order to establish the typical size and shape of features. A global database of Quaternary maar crater planform morphometry indicates that maar craters are typically not circular and frequently have compound shapes resembling overlapping circles. Maar craters occur in volcanic fields that contain both small volume and complex volcanoes. The global perspective provided by the database shows that maars are common in many volcanic and tectonic settings producing a similar diversity of size and shape within and between volcanic fields. A few exceptional populations of maars were revealed by the database, highlighting directions of future research to improve our understanding on the geometry and spacing of subsurface explosions that produce maars. These outlying populations, such as anomalously large craters (> 3000 m), chains of maars, and volcanic fields composed of mostly maar craters each represent a small portion of the database, but provide opportunities to reinvestigate fundamental questions on maar formation. Maar crater morphometry can be integrated with structural, hydrological studies to investigate lateral migration of phreatomagmatic explosion location in the subsurface. A comprehensive

database of intact maar morphometry is also beneficial for the hunt for maar-diatremes on other planets.

Keywords: maar; crater morphometry; elongation; lateral crater growth; global database

1.0 Maar craters

Phreatomagmatic explosion processes can occur in any volcanic system, but the products of these processes are easiest to study at small volume volcanoes dominated by these explosions. Maar craters are the end-member product of phreatomagmatic-dominated eruptions and present a distinctive landform for remote morphometric analyses. Morphometry of young volcanic features reflects both surface and subsurface processes of an eruption. A comparison of a large population of volcanic constructs can establish the typical size and shape of craters as well as any trends between the landform and local and regional influences such as volcanic setting, hydrology, and topography. To recognize universal characteristics of craters formed by subsurface phreatomagmatic explosions, a global database of young maar crater size and shape was created: Maar Volcano Location and Shape (MaarVLS). The size of maars have been previously described in a few studies, but the source data for larger datasets was unavailable (Cas and Wright, 1987), the measurements are limited to a few isolated craters (Nemeth et al., 2001), or were limited to highly eroded craters or diatremes (Martín-Serrano et al., 2009). This database contains the data of maar sizes and shapes from multiple eruptive fields from a range of volcanic settings. This study focuses on pristine morphology and thus does not contain morphometric data from all known maars; however, the discussion here also considers other recognized features from the literature to apply morphologic observations to our understanding of maar formation. This global survey of maars enables the study of bigger picture processes of these volcanoes including influences on crater growth, implication of crater shape, and the diversity of features within in and between volcanic fields.

A maar is a volcanic crater cut into the ground surface produced by tens to hundreds of discrete subsurface explosions resulting from the interaction of magma and groundwater. The craters are surrounded by low angle tephra rings composed of ejecta from these explosions. The dominant morphological feature of these landforms is the crater rim (Fig. 1). Maars are underlain by crudely funnel-shaped structures full of pyroclastic and country rock breccias called diatremes. Maars exhibit shifts in eruption style: starting with, alternating with, or ending with magmatic volatile-driven activity (e.g. White and Ross, 2011). Eruptions with increasing contributions from magmatic explosions form more constructional landforms such as tuff rings and tuff cones that have steeper flank slopes or overlapping scoria cones. This study focuses on craters produced by explosive excavation of host rock by phreatomagmatic explosions to produce a crater (maar) and aims to avoid interpretations relating to the available water content. As these landforms occur along a spectrum and crater infill frequently makes depth measurements difficult, the database is inclusive of features with evidence of subsurface excavation. To be included in the database a crater must be previously documented as a phreatomagmatic construct based on field observations and meet criteria relating to age and suitability for remote analysis (Table 1). Craters must be recognizable in satellite imagery (visible or topographic), be Quaternary in age, and have a nearly complete to complete crater rim. Consequently, some features included in the database may have been called a tuff ring or cone by previous researchers because of the slope of the tephra ring deposits, but otherwise meet the morphologic definition here. The use of references prevented the inclusion of any known calderas, though recent work has highlighted that these features may have more in common than previously recognized (Palladino et al., 2015).

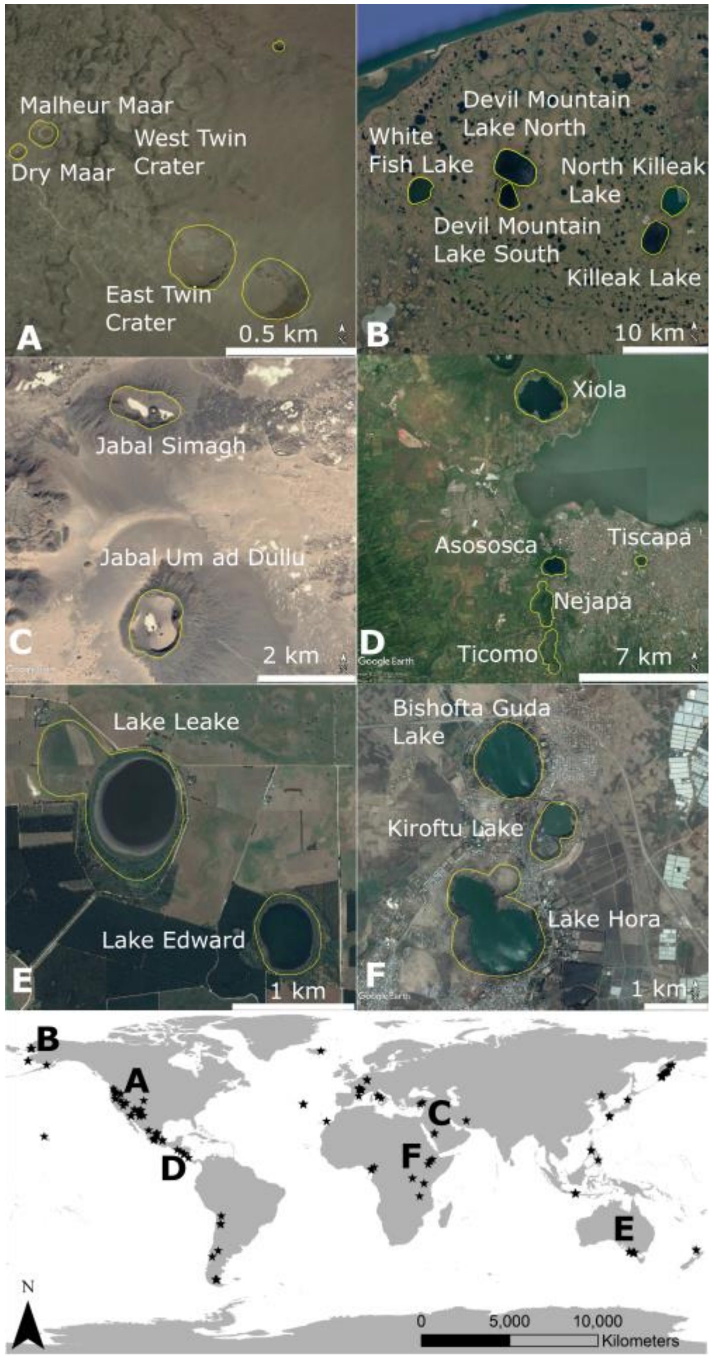

Figure 1 Examples of maar crater shape diversity from the MaarVLS database with yellow lines indicating the crater rim with locations of craters in the database. Locations of featured craters noted with a letter on the map. A) Diamond Crater USA including the smallest (69 m diameter) Dry Maar. B) Espenberg Craters on Seward Peninsula AK, USA are the largest craters in the database (4-5 km diameters). C) Jabal Simagh of the Harrat Kishb field in Saudi Arabia has an AR values of <0.5. D) Nejapa and Ticomo maars in Nicaragua have elongation values of <0.45. E) Lake Leake of Newer Volcanic Province, Australia, and F) Hora Lake Bishoftu Volcanic Field, Ethiopia show off the range of isoperimetric circularities in the database. Images courtesy of Google and Digital Globe and CNES/Astrium.

Table 1: Summary of characteristics of maar volcanoes used for recognition, inclusion in the database and a revised list based on observations from the database

Defining characteristics	**Other criteria**
For initial recognition	*For inclusion in database*
Negative landform that cuts into the ground surface	Recognized in satellite imagery including topographic datasets
Raised rim that extends away at low slope angles	Have documented field identification as a maar or fitting the description of a maar including tephra ring deposits
Rim and tephra ring composed of layers of volcaniclastic debris	Included in a publication such as peer-reviewed paper, maps or governmental information websites that can be referenced
Small <10 km in diameter	Quaternary in age
Frequently occurs in volcanic fields	Rim must be complete or nearly complete (>75%)
Additional characteristics derived from database	
Commonly elongate	
Commonly displays irregularities in curvature	
69-6000 m with most between 600-1000 m diameter	
Occur with other volcanoes either in complex or small volcano dominated fields	
Individual volcanic fields containing maars have a range of shapes and sizes	

The bulk of the explosive activity and deposits of a maar-diatreme occur in the subsurface. As such, for young maars, the eruption, including depth and lateral position of explosions, can only be reconstructed from the deposits that were successful ejected from the crater to reach the tephra ring, and the shape of the crater. Maar craters grow through a combination of explosive excavation and collapse (White and Ross, 2011; Sonder et al., 2015; Graettinger et al, 2016). The crater rim is only partly a constructional feature and therefore crater shape, as measured here, is less susceptible to influences of outer slope stability and wind than for scoria and tuff cones (Kereszturi et al., 2012; Kervyn et al., 2012; Bemis and Ferencz, 2017). These observations suggest that maar crater shape for intact crater rims retains a signature of crater growth by eruptive and syn-eruptive processes.

Detailed studies of exhumed diatremes (Lefebvre et al., 2013; Delpit et al., 2014) and geophysical investigations (Blaikie et al., 2012; Jordan et al., 2013) have revealed the complexity of diatremes that can involve multiple coalesced cones of debris and reach depths of up to 2 km (White and Ross, 2011). The excavation and coring of kimberlite pipes have also documented overlapping diatreme structures (Kurszlaukis et al., 2009). All these observations point to a complex history of magma transport and interaction with the host during these eruptions. Further, the geophysical studies indicate that this subsurface complexity is linked to surface complexity of maar crater shape (Jordan et al., 2013). Experimental work has investigated this idea further by determining the relative distance of subsurface explosion positions and the production of circular, complex, and independent craters (Valentine et al., 2015a). This study aims to quantify natural maar shapes and evaluate the potential for reconstructing the number and geometry of lateral explosion locations in the subsurface.

As with any geologic study, it is important to outline terminology and set apart descriptive terms from genetic terms. The term crater here refers to the final landform, while vent is used for locations where material is ejected during an eruption. Multiple vents can be located in a single crater. This study uses the term compound crater to describe craters that have the appearance of multiple overlapping circles, with no indication of whether that crater formed during one eruptive period or several co-located eruptions separated in time. The term septum (plural septa) describes a raised ridge between low points in a compound crater. The term coalesced is avoided due to its inconsistent use in the past as both describing shape and reflecting a polygenetic history. There are cases where field evidence indicates that a final maar crater was the product of two or more eruptions separated in time that were co-located to produce a single landform. Craters are documented in the database as the product of multiple eruptions only if there is evidence of eruptive deposits separated by time, such as paleosols or dated eruption units. This categorization here has no further implications about the longevity of the single magmatic system that can be connected to the term polygenetic. In the same way, discrete crater features that were produced in a single eruption (Ukinrek and Ubehebe) are included as separate entries as this study focuses on shape.

The MaarVLS database includes manually digitized crater outlines, size, and shape parameters with preliminary additional information on tectonic setting, volcanic field characteristics, composition, elevation, and age. MaarVLS currently contains 240 maar craters identified in published literature as Quaternary, between -60 to 70 degrees latitude, from 65 different volcanic fields (Fig. 1). The maars are predominantly mafic in composition, but five rhyolite and seven intermediate composition maars are included. The database includes historic, Holocene, and Pleistocene maars.

MaarVLS has room for further growth in terms of number of volcanoes and contextual information as new studies are conducted or data becomes available. The database is available on Vhub.org, an online platform for collaborative volcano research and risk mitigation, and will be updated periodically as additional submissions are collected. MaarVLS is currently a spreadsheet containing 31 categories for each crater (Table 2). All craters have name and variants, Global Volcanism Program number, latitude, longitude, country, area, perimeter, major axis, minor axis, average diameter, aspect ratio, elongation, isoperimetric circularity, volcanic field name, elevation, and references. Other categories are as complete as current literature allows and include age, composition, depth, population at 5 and 100 km distances, and whether there is evidence of multiple co-located eruptions.

Table 2: Contents of MaarVLS database.

Contents	**Details**
Crater	Name, alternate name, volcano number (GVP), country
Location	Latitude and longitude of centroid using WGS-84
Shape measurements	Major axis, minor axis, average diameter (average of 2 axes), perimeter of crater, area of crater, shape type[1]
Topography[2]	Depth, depth to diameter ratio, presence of septa
Context[2]	Elevation, land use, tectonic setting, volcanic field type, occurrence with other maars, volcanic field name, age, evidence for multiple co-located eruptions separated in time, composition, underlying geology, population within 5 km and 100 km of volcanic field
Morphometry	Aspect ratio, elongation, circularity, depth to diameter ratio
Reference	List of references used to populate the database for a given crater

1 Polygon or shape file to indicate if the data was collected from Google Earth or using individual images in Arc GIS respectively.
2 Based on available literature, to be expanded in later versions.
Elevation is measured by the level of the lake or low point of the crater.

MaarVLS provides a global perspective on maar craters and highlights potential for comparative studies between multiple volcanic fields. This study identifies the unique morphometric characteristics of maars that can be used to distinguish them from other similar negative landforms such as kettle and permafrost lakes, impact craters, karst features and volcanic collapse pits, and can ultimately be used to identify similar volcanic features on other planets, such as Mars (Graettinger, 2016).

2.0 Methods

Maar craters were selected from existing literature in areas where satellite imagery was most readily available. Literature here includes peer-reviewed articles, edited books on volcanic regions, the Global Volcanism Database (Global Volcanism Program), field trip guides, city and federal government informational websites, and USGS or US National Parks Service publications and maps. The references for individual craters are included in the database and a comprehensive reference list accompanies the database (Supplemental information). Craters were initially located using published coordinates and maps, and then added to a Google Earth .kml file and evaluated for morphometric analysis. Google Earth uses a cylindrical projection that has significant warping at the poles. This first version of the database only includes craters above 60 degrees latitude when alternative datasets such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery were already available in the author's collection. Future versions of the database will take advantage of publicly available ASTER imagery and other open datasets to include a larger population of maar craters at high latitudes. All craters are Quaternary in age and have complete, or near complete (>75%), rims with limited incision by erosion (Table 1). Craters that have interacted with scoria cones or lava flows were generally avoided, unless the 75% unobstructed crater rim criterion was satisfied. Compound craters with > 3 separated basins are not included in the first version of the database due to the high level of interpretation required for digitization (i.e. Katwe Volcanic Field, Uganda; Murray and Guest, 1970). Modification by human activity is common for many of the volcanic fields studied. When human activity made an obvious impact on the crater rim (i.e. quarrying), the crater was not included in the database.

Craters were outlined manually from visible Google Earth imagery, ASTER images and digital elevation models to produce polygons encompassing the crater along the rim. Crater outlines were completed by four individuals and evaluated by one researcher for consistency. Polygons of crater outlines were used to determine area, perimeter, and length of major and minor axes. An average of the two axes is used as average diameter in this study. Shape parameters were derived for each crater from these measurements. Shape parameters used in this study describe the two-dimensional shape of the outline of the crater from the digitized polygon. These include dimensionless ratios: aspect ratio, elongation, and isoperimetric circularity. Aspect ratio (*AR*) is defined as the ratio of a crater's diameters:

$$AR = \frac{\mathrm{Dminor}}{\mathrm{Dmajor}} \quad (1)$$

where D_{minor} is the length of the crater's minor axis and D_{major} is the length of the crater's major axis. Here the minor axis is measured as the axis perpendicular to the major axis running through the center point. An aspect ratio of 1 represents an equant shape around the center point; as the disparity between the two axes increases, the aspect ratio decreases away from 1.

Elongation (*EL*) is defined:

$$EL = \frac{\mathrm{A}}{\pi(\frac{\mathrm{Dmajor}}{2})^2} \quad (2)$$

where *A* is the area encompassed by the crater rim as defined by the digitized polygon. Elongation compares the area of a circle with the diameter of the major axis to the maar area. A circle has Elongation equal to 1 and more elongate shapes have smaller values. Elongation differs from Aspect Ratio as it better describes asymmetrical shapes, in fact, for ellipses the two values will be the same.

Isoperimetric Circularity (*IC*) is defined as the area of a crater polygon divided by the area of a circle with the same perimeter.

$$IC = \frac{4\pi A}{P^2} \quad (3)$$

where *A* is the area encompassed by the crater rim and *P* is the perimeter of that same polygon. Isoperimetric Circularity is a measure of the variation in curvature of the outline of a shape. A shape with a single constant angle of curvature, like a circle, has an Isoperimetric Circularity of 1 and shapes where the angle of curvature varies will have Isoperimetric Circularity <1.

Depth measurements for craters were collected from the literature, using topographic data such as the Earth Point topo map of the US, published topographic maps of field areas, and estimates in publications or from local governments (city, state/province) or national parks. These values are only as accurate as their source material and therefore have an uncertainty of at least 10 m. Due to the presence of lakes, inconsistent reporting, post-eruption modification by erosion, human or volcanic activity, and low resolution data, maximum depth measurements reported are minimums. Where the measurement reflects only the surrounding rim, or only lake depth, a notation is included in the database. Depth to diameter ratio (*d/D*) was calculated for craters when possible using the available values for depth by the major axis and is consequently a minimum value. Elevation is recorded at the base of the tephra ring or the surface of lake in the maar as available, and other available published estimates. Due to limited data availability, some volcanic fields have single elevation reported across the field. No values are expected to be off by more than 200 m. Although not useful for in-field evaluations, these values are sufficient for preliminary evaluation and will be an area of improvement in later versions of the database. This study addresses quantitative size and shape parameters, latitude and longitude, elevation, composition, and when possible, age of maar craters. Volcanic fields that host maars are discussed based on the maars included in the database (with well-preserved morphologies), and not total population.

3.0 Results

3.1 Size and Shape

Mean crater diameters, the average of the two major axes, in MaarVLS are 69-5000 m. Major axis measurements reach up to 6100 m, and minor axes measurements reach 4300 m. The smallest maar, the 69 m mean diameter Dry Maar, occurs in the Diamond Craters field in Oregon, USA (Wood and Kienle 1990; Fig. 1a). The largest maar, the 5013 m mean diameter Devil Mountain Lake North, occurs in the Espenberg volcanic field in Alaska, USA (Beget et al. 1996; Fig. 1b). Most maar craters have diameters 600-800 m (Fig. 2); 75% of the average crater diameters are <1295 m. Crater areas average 1.5 km^2, with perimeters of 0.2-16 km. The smallest maars (<200 m, <3% of database) occur in close proximity (<600 m) to other maar craters including the Ukinrek West crater (Self, 1980) and Crater Z at Ubehebe (Fierstein and Hildreth, 2017). In several cases these small craters are interpreted to be part of the same eruptive sequence as the adjacent craters (Self, 1980; Fierstein and Hildreth, 2017). Very large craters (>3000 m diameter and area >7 km^2) represent only 4% of the maar population.

Available values for maar depths range 5-400 m with an average depth to diameter ratio of 0.10. However, depth estimates are poorly constrained with error estimates of ~20 m due to the presence of lakes and abundance of sedimentary infill. For the 113 craters in the database with both depth and age data, there is no apparent trend of depth with age (Fig. 3). As depth is susceptible to post-eruption infill (Pirrung et al., 2008), subsidence (White and Ross, 2011), and human modification, preserved depth is not reflective of eruption history and therefore not discussed further in this analysis. Only 7% of the craters in the database have septa separating the circular elements of the crater shape (e.g. Ticomo, Nicaragua; Figure 1; Avellan et al., 2012). In craters without septa the lowest point is frequently off center and some compound craters have a stepped topography (e.g. Kiroftu Lake, Ethiopia; Gasparon, 1993).

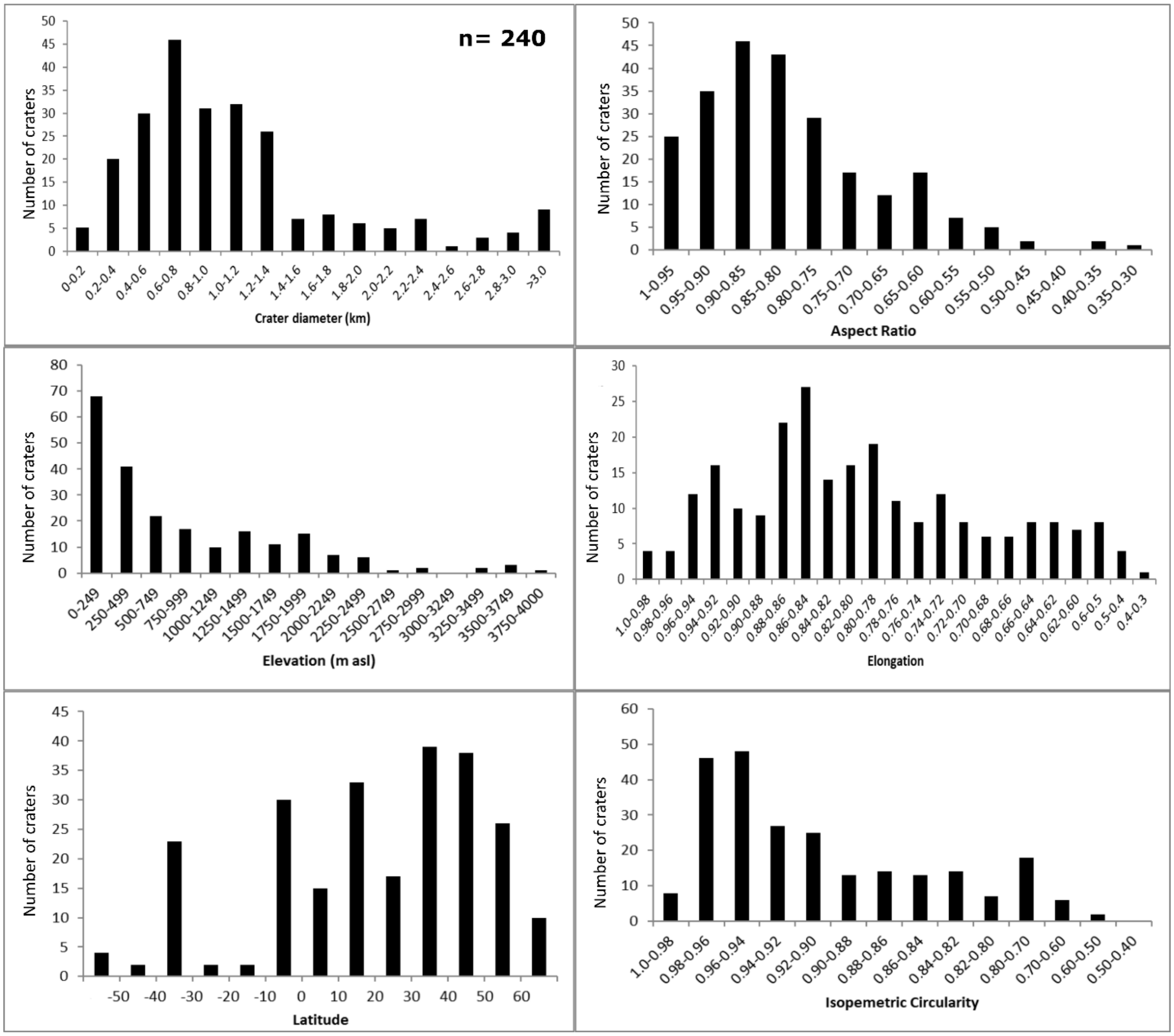

Figure 2 Histograms of craters in MaarVLS version 1 database including size, distribution and shape. The total number of crater is 240.

Aspect ratio is a measure of the disparity between the major and minor axis (Equation 1). Maar craters have an average Aspect Ratio of 0.81 with most values between 0.80-0.95 (Fig. 2). Less than 11% of maars have an Aspect Ratio >0.95 reflecting an equant shape.

Extreme low values of Aspect Ratio (0.3-0.5) describe only 2% of the database (e.g. Jabal Simagh Saudi Arabia; Fig. 1c).

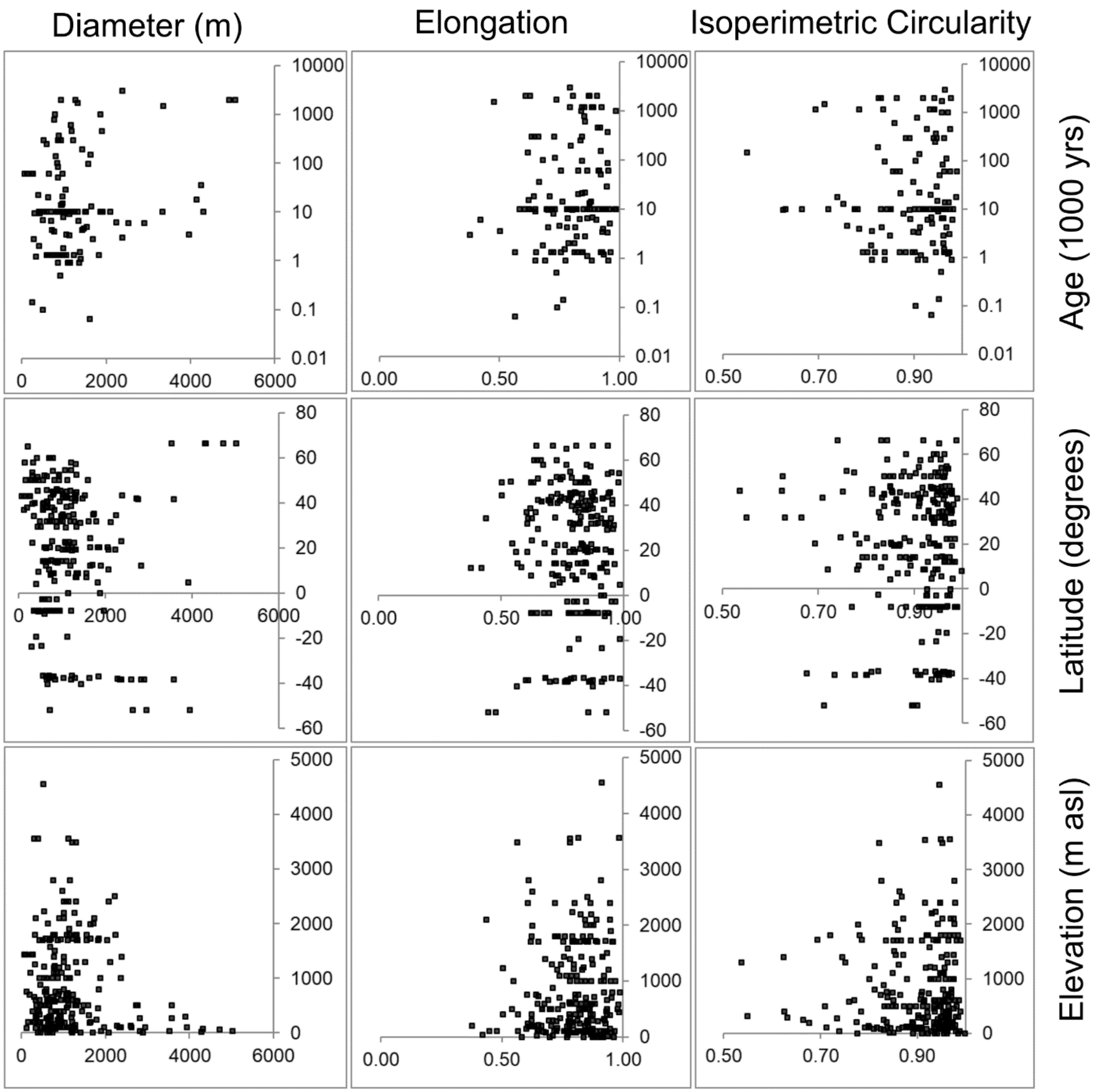

Figure 3 MaarVLS crater shape and size parameters relative to distribution (elevation and latitude) and age. The diameter is the crater average. Elongation of a circle is 1.0 and more elongate shapes >1.0. Isoperimentric circularity of a circle is 1.0 and less circular shapes are <0. There are no distinct trends between shape and size with age. Small craters occur at all latitudes and elevations but exceptionally large craters are found predominantly at high latitudes and low elevations.

Elongation compares the area of the maar to the area of a circle with the diameter of the major axis (Equation 2). The craters in the database have a wide range of Elongation, averaging 0.80 with a standard deviation of 0.12 and most values between 0.88-0.84 (Fig. 2). In MaarVLS 85% of craters have Elongation values less than 0.92. Extreme values of Elongation (<0.50) reflect only 5% of the database (e.g. Nejapa Maar, Nicaragua; Fig. 1d).

Isoperimetric Circularity is a measure of the variation in curvature of the outline of a shape with values 0-1 with 1 being a circle. (Equation 3). Maar craters in the database have a limited Isoperimetric Circularity, with average values of 0.9 and standard deviation of 0.08. Most (65%) craters have an Isoperimetric Circularity 0.9-1 (e.g. Lake Leake, Australia; Fig. 1e; Boyce, 2013) with only 9% of craters having a value below 0.80 (e.g. Hora Lake, Ethiopia; Gasparon 1993; Fig. 1f). Maar craters with Isoperimetric circularity values <0.9 display a compound shape, similar to multiple overlapping circles (Fig. 4) resulting in a few larger scale variations in curvature. There is no apparent trend with size for any of the shape parameters (Fig. 3). There is not a diagnostic crater shape related to craters produced by multiple co-located eruptions or long-lived polygenetic eruptions. This relationship will need to be reevaluated as more dates become available for these volcanic systems.

These shape values can be compared with ellipses that vary by the relationship between the major and minor axis (Fig. 4). The average Aspect Ratio and Elongation of maars in the database can be reproduced by an ellipse with a major diameter >1.2 times that of the minor diameter. These ellipses, however, both have greater Isoperimetric circularity values than the average maar crater. Additionally, most maars do not have equivalent AR and EL values the way that ellipses do. Natural maars commonly have compound shapes resembling overlapping circles or embayed ellipses. A series of simplified shapes with AR, EL and IC values close to the database average illustrates how the shape values respond to symmetry and curvature variations (Fig. 4) common in the database.

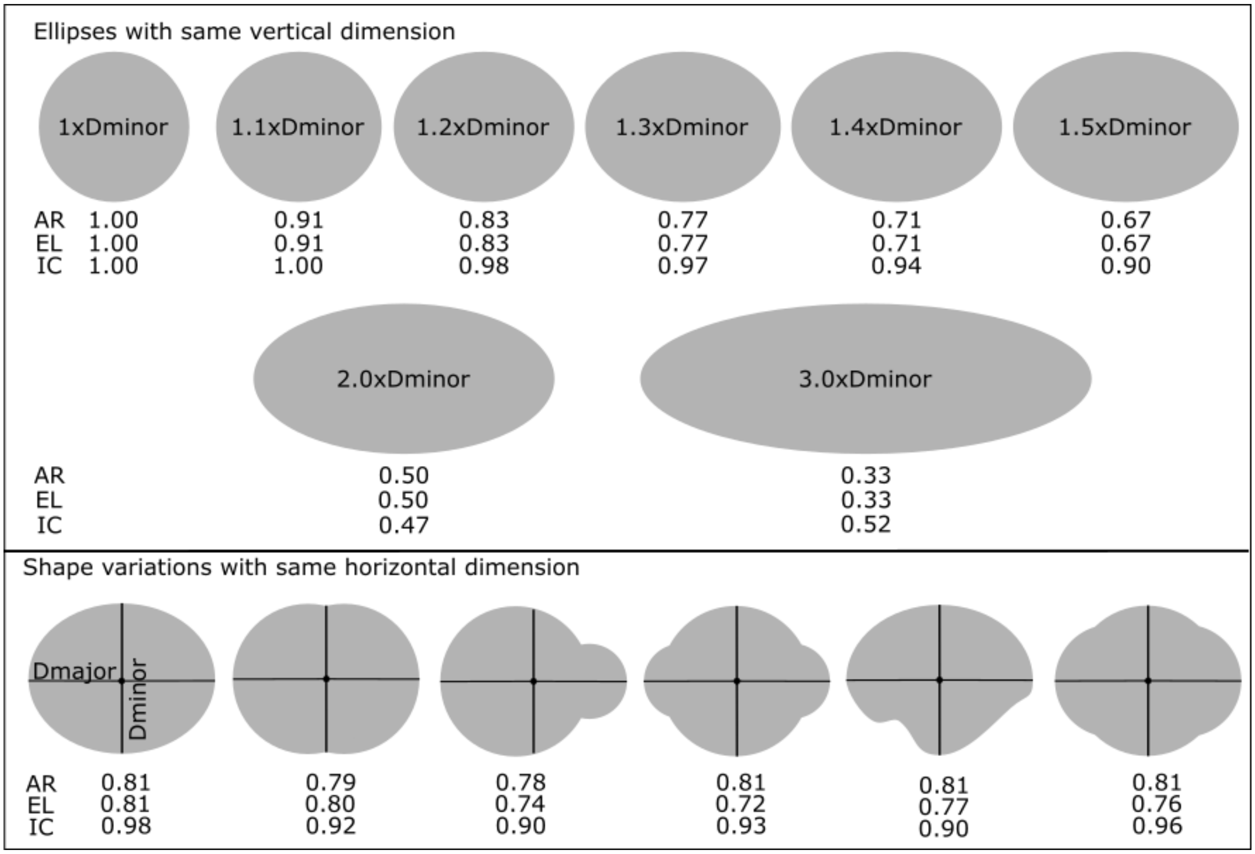

Figure 4 Idealized shapes that illustrate how shape parameters vary with shape complexity. Ellipses where the maximum diameter increases relative to the secondary diameter (D_{minor}) show how aspect ratio and elongation decrease drastically with exaggerated ellipses. AR and EL values <0.5 are considered extreme and represent less than 5% of the database. The AR values from the database correspond to ellipses with major diameters 1.1-1.3 times that of the minor diameter, but the isoperimetric values require changes in curvature of the shape as exemplified by the lower shapes.

3.2 Distribution

Maar craters occur in 1) monogenetic fields with similar sized volcanic features such as scoria cones (56% of database), 2) in complex volcanic fields containing small volcanic vents alongside, on, or, in larger structures such as stratovolcanoes and calderas (42%), and 3) in rare cases, in isolation. Over 96% of craters in the database occur in fields with other maars, where 71% of craters occurred in fields with more than five maars. While roughly half of the maars in the database occur in intraplate volcanic settings, they are also found in back arc basins along subduction zones, continental rifts, on ocean islands above hot spots, and less commonly in convergent or transpressional environments.

Maars in the database occur at sea level to elevations as high as 4000 m above sea level (asl). At higher elevations the number of documented maars decreases, with most (90%) below 2000 m asl (Fig. 3). Maars in the database cover a range of latitudes, but do not have even distribution across all latitudes (Fig. 2). Maars above 200 m all occur between -30 and 40 North latitude. A comparison of crater diameter with distribution reveals that small craters (<1000 m) occur globally at all elevations (Fig. 3), however, all exceptionally large maar craters (diameter >3000 m, area >7 km^2) occur at elevations below 500 m asl. Crater shapes do not present a clear trend with latitude, but isoperimetric circularity does increase (craters are more circular) with increasing elevation (Fig. 3).

3.3 Fields

Quaternary volcanic fields with maar volcanoes contain anywhere from one to tens of maar craters. In MaarVLS several fields are currently represented by only a sample of maars due to limitations in available imagery, and the complete crater rim criterion. For volcanic fields with five or more included maar craters, the size variability within individual volcanic fields is high, but lower than the database as a whole (measured in meters; total stdev=861, for fields with maars stdev=395; Table 3). Within a volcanic field, craters will typically fit between a minimum and maximum crater diameter ratio of 0.36, meaning that the largest crater is less than twice the diameter of the smallest crater. The shapes of craters within these volcanic fields have similar average shape parameters, but narrower ranges than the overall database (Table 3).

Table 3: Comparison of maars globally to trends by volcanic fields containing maars.

	Average diameter (m)	Aspect Ratio	Elongation	Isoperimetric circularity	n	Diameter range (m)	Min dia/ Max dia ratio
MaarVLS	1122+/-833	0.81+/-0.13	0.80+/-0.12	0.90+/-0.08	240	4945	0.01
Mode	603	0.84	0.62	0.93			
50 percentile	905	0.83	0.82	0.93	240		
Fields containing 5 or more maars	1179+/-395	0.81+/-0.05	0.79+/-0.05	0.90+/-0.04	5*	1148	0.36
Mode	600-800	0.75-0.85	0.79-0.80	0.85-0.95	2-19**		

Values are averages +/- one standard deviation or represent a range.
Volcanic fields used for this analysis: Auckland Volcanic Field (NZ), Bishoftu Volcanic Field (Ethiopia), Chaine des Puys (France), Diamond Craters (USA), Eifel Volcanic Field (Germany), Lake Natron-Engaruka field (Tanzania), Lamongan (Indonesia), Long Gang (China), Newberry volcanic region (USA), Newer Volcanic Province (Australia), Pinacate Volcanic Field (Mexico), Qal' eh Hasan Ali (Iran), San Pablo Volcanic Field (Philippines), Serdán Oriental (Mexico), Espenberg Volcanic Field (USA).
*Average value for all volcanic fields in the database containing more than one maar.
** Range of values for the number of maars in fields with more than one maar in database.

The database also provides an opportunity to investigate the distribution of maar craters relative to population centers (Table 4). Based on population data 2013 as recorded by GVP six volcanic fields with more than 5 Quaternary maars occur within 5 km of >100,000 people. The Auckland Volcanic Field in New Zealand, Nejapa-Miraflores Field in Nicaragua, and San Pablo City Volcanic Field in the Philippines are within 5 kilometers of more than a million people. These population values should be considered conservative estimates as urban populations are growing globally and areas like Addis Ababa close to the Bishoftu Volcanic Field in Ethiopia, have large undocumented populations not reflected in these estimates.

3.4 Age

Age constraints are available for 53% of the database (n=127), and only half of those are isotopic techniques applied to the maar deposits, stratigraphically bounding units or historic observations with the remainder being based on morphology and comparisons with features in the same volcanic field. However, as individual volcanic fields containing multiple maar craters (e.g. West Eifel Volcanic Field, Zolitschka et al., 1995) are well dated, the preliminary trends between crater size, shape and distribution with age were evaluated. There is no apparent correlation between maar crater age with latitude, elevation, diameter, elongation or isoperimetric circularity (Fig. 3).

Table 4: Volcanic fields containing multiple maar volcanoes occur near large population centers around the world. Populations within 5 km of maars and maar fields are at risk of primary eruption hazards such as ballistic fall and pyroclastic density currents.

Name	N[a]	# of vents[b]	Min Diameter (m)	Max Diameter (m)	Population within 5 km[c]
Auckland, New Zealand	**7**	**53**	**333**	**1229**	**1,500,000**
Bishoftu, Ethiopia	6	>20	766	1556	300,000
Chaine des Puys, France	9	141	440	1336	300,000
Eifel, Germany	11	224	158	1593	90,000
Lake Natron-Engaruka, Tanzania	5	200	550	871	low
Lamongan, Indonesia	19	90	349	1211	>5,000
Long Gang, China	5	>150	742	1125	30,000
Nejapa-Miraflores, Nicaragua	5	>10	622	2824	**2,200,000**
Newberry, USA	6		789	2379	<100
Newer Volcanic Province, Australia	13	416	640	3582	<600,000
Pinacante, Mexico	9	>400	650	1782	<100
Qal'eh Hassan Ali, Iran	5	5	438	1333	5,000
San Pablo, Philippines	**12**	**tens**	**564**	**1268**	**1,300,000**
Seridán Oriental, Mexico	8	tens	1010	2218	90,000
Seward, USA	5	5	3532	5013	Low
Kamchatka, Russia	12	100's	312	1339	Low

[a] number of maars in field included in the MaarVLS database, represents a minimum value for maar population within the volcanic field.
[b] number of vents (all types) in the field from GVP, LeCorvec 2013; Mattson and Tripoli 2011; Carn 2000; Boyce 2013; Gutman 2002; Milton 1977.
[c] Population data from GVP 2013 and are rounded down to the nearest 5,000 to provide relative numbers rather than precise population values. Population values for Nejapa-Miraflores updated to reflect 2015 population of Managua.

3.5 Composition

Compositional data are available for 60% of the database (n=146). Most maars in MaarVLS were formed by mafic magmas, with high alkali contents common. Five confirmed rhyolitic maars and seven intermediate maars are included in this first version of the database. The rhyolitic maars are all larger than 1000 m in diameter, but are not distinctively larger than mafic maars as a population (Table 5). Intermediate magmas form maar craters 360-1400 m across and fit within the scatter of mafic maar sizes. The shape of intermediate and rhyolite maars is typically more circular and less elongate than mafic maars, but not enough to be diagnostic. The largest craters (>3000 m) are limited to mafic magma compositions. Therefore, based on this population, composition cannot be determined solely from crater size or shape.

Table 5: Comparison of size and shape trends for maars with known magma compositions.

	Average diameter (m)	Aspect Ratio	Elongation	Isoperimetric Circularity	n	Diameter range (m)	Min dia/ Max dia ratio
Mafic	1236 +/- 1023	0.80 +/- 0.14	0.79 +/- 0.13	0.90 +/- 0.08	134	4945	0.01
Intermediate	760 +/- 516	0.86 +/- 0.08	0.87 +/- 0.07	0.90 +/- 0.05	7	1479	0.20
Rhyolite	2017 +/-923	0.91 +/- 0.08	0.88 +/- 0.08	0.96 +/- 0.03	5	1814	0.36

Values are averages +/- one standard deviation or represent a range.

4.0 Discussion

The MaarVLS database enables several generalizations about maar crater size and planform shape that were previously not possible due to the absence of a global dataset. Maar craters are typically elongate, but not simple ellipses, having large-scale variations in curvature that frequently resemble overlapping circles. Although compound shapes are common, septa separating topographic lows are rare (or rarely preserved), and the organization of the overlapping circles is variable across maars and volcanic fields with maars (Fig. 1). A few anomalous populations of maar size (exceptionally large) and morphology (crater chains) stand out against the main database characteristics. The database also highlights that while maars typically represent a fraction of the volcanic constructs within a volcanic field there are a few notable exceptions with abundant maars. Further, the maars studied occur in a wide range of volcanic field types and tectonic settings reinforcing that while the conditions that form maar volcanoes are specific, they are not limited to only one environment. Further, the global distribution of maars highlights the proximity of numerous maar fields to major population centers. In order to evaluate the potential for interpreting subsurface maar forming processes, namely explosion location and number, from crater shape it is necessary to evaluate post-eruption modification, the completeness of the sample population, and the exceptional maar populations mentioned above.

4.1 Role of post-eruption modification

Investigations of crater modification from the 1977 eruption of Ukinrek in Alaska revealed a rapid increase in the major and minor axes of the crater and infill of the crater floor initially after the eruption and stabilization with time (Pirrung et al., 2008). The shape of the crater however, as measured by aspect ratio, was maintained. This suggests that absolute crater diameters, depth, and internal slopes are susceptible to modification by erosion, but crater shape is more stable over time. As the inclusion criterion for MaarVLS excluded maar craters such as Kilbourne Hole, New Mexico, and Fort Rock, Oregon where the crater rim was interrupted or missing, the shapes within the database are assumed to represent post-eruptive shapes. Furthermore, comparison of Aspect Ratio, Elongation, and Isoperimetric Circularity for those maars in the MaarVLS database with age indicates that there is no trend in crater shape with age for Quaternary maars (Fig. 3).

Unlike scoria cones, which are constructional features with steep slopes, maar craters have low angle tephra rings that extend away from the crater with the main structure cut into the ground surface. When maars are erupted on complex topography this tephra ring will roughly drape the surrounding topography (e.g. Dotsero, Leat et al., 1989; Bea’s Crater, Amin and Valentine, 2017). The crater is the result of excavation and collapse with limited deposits escaping the crater to form the low angle tephra ring (Graettinger et al. 2016). The shape of the crater is therefore less susceptible of the influence of outer slope stability and wind than for scoria and tuff cones (Kereszturi et al., 2012; Kervyn et al., 2012). The low slope angle of the tephra rings enables agricultural activities with less earth works than scoria cones or lava flows, and consequently many roads and farms merely mantle the tephra ring deposits preserving crater rim morphology. Based on these observations, for maars included in the database it is reasonable to assume the crater shape, and to a lesser degree crater size, is dominated by a signature of crater growth by eruptive and syn-eruptive processes.

4.2 Completeness of coverage

MaarVLS contains craters from a range of latitudes, with fewer craters at latitudes greater than 60 degrees. High latitudes in both hemispheres are under-sampled as additional imagery is required (due to warping of projections at the poles in WGS84 used in Google Earth) and will be used to produce future versions of the database. The southern hemisphere is represented by 64 craters, with limited craters from -10 and -20 degrees (Fig. 2). As the southern hemisphere contains ~30% of the continental crust on Earth, the database has a roughly proportionate distribution of maar craters between the hemispheres. Maar craters are observed at a wide range of elevations (0-3500 m asl), but 60% of maars are at elevations of 1000 m or less, with half of that being at elevations below 250 m. As 75% of elevations above sea level on Earth are less than 1000 m (Eakins and Sharman, 2012) the low abundance of maars at high elevation is to be expected (Fig. 2). The number of craters included in the database and the large range of elevations and latitudes on Earth provides a sufficiently diverse population to establish what is typical of maar crater size and shape (Section 3.1) to recognize any exceptional populations of maars on Earth (Fig. 2-3).

4.3 *Unique populations*

Very large craters

Of the shape parameters evaluated, diameter (Fig. 2) and area are the only parameters to highlight a distinct outlying population. Very large maars occur in six volcanic fields that are globally distributed, but all occur at low elevations (Fig. 5). The Espenberg maars (Beget et al., 1996) in Alaska, USA, and Pali Aike maars in Argentina (Ross et al., 2011) both include multiple craters >3000 m in diameter that are thought to have erupted through permafrost based on field observations. Field studies have indicated that soft host rock may lead to larger crater diameters (Auer et al., 2007), however the size of these craters far exceeds the database norm and the size of other maars formed in unconsolidated sediment. These large high latitude maars suggest that the distribution and physical state of water in the host rock may also be significant to crater size and shape. In particular, the nature of the host rock influences the availability and transport of water within a diatreme required for phreatomagmatic explosions. Because the extent of permafrost during past glaciations is not well constrained and maar age dates are still sparse there may be additional craters (of any size) that formed in a glacial or periglacial environment. The role of ground ice in the formation of maars is an important area of exploration on Earth and on Mars.

The majority of the remaining >3000 m maars occur in complex volcanic fields including Colli Albani in Italy and Kumba in Cameroon, and show evidence of multiple eruption deposits separated by paleosols (Sottili et al., 2009; Chako Tchambe et al., 2015). All maars in the database with evidence of multiple co-located eruptions are > 1000 m in diameter (Nemeth and Kereszturi, 2015; Jordan et al., 2013; van Otterloo et al., 2013; Isaia et al., 2015; Valentine et al., 2015b), but not all large craters show evidence for multiple eruptive episodes (e.g. Espenberg maars, Beget et al., 1996). Those craters that have experienced multiple co-located eruptions occur in both continental rift settings like the Kumba field and in back arc basins such as the Nejapa maar in Nicaragua (Avellan et al., 2012). Maars produced by co-located eruptions occur with other small volume volcanoes in the Newer Volcanic Province, Australia (van

Otterloo et al., 2013), and in conjunction with long-lived composite volcanoes like the Sabatini District in Italy (Valentine et al., 2015b). The Newer Volcanic Province hosts several large maars, some exceeding 3000 m in diameter, however additional work is required to determine if they were all the product of multiple co-located eruptions. The relationship between exceptionally large maar craters and their eruptive hazards including duration, potential for repeat eruptions and scope of eruption, warrants further exploration in these and other volcanic fields.

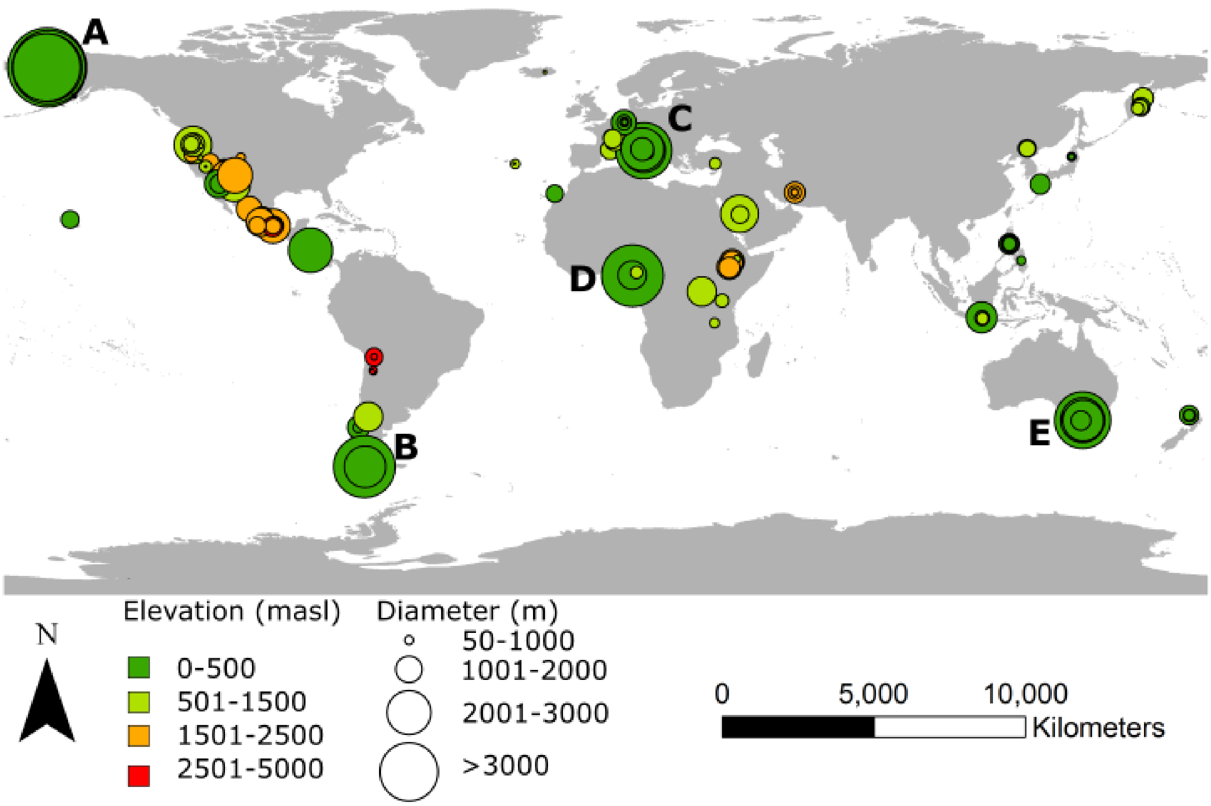

Figure 5 Crater size (average diameter) and elevation plotted geographically with one symbol per maar, but significant overlap occurs due to the size of the map. Labeled fields host very large maar craters (>3000 m diameter) A) Espenberg maars, B) Pali Aike Volcanic Field, C) Colli Albani Volcanic Region, D) Kumba Volcanic Field, E) Newer Volcanic Province. Large maars all occur below 500 masl.

Chains of craters

An additional subgroup of maar craters resemble chains of closely spaced or connected craters with associated extreme values of Elongation and Aspect Ratio. The Asososca, Nejapa, and Ticomo maars in Nicaragua south of Lake Manuagua, occur along a linear trend that could be extended to include the Xiola maar to the north (Fig. 1d). Within this set of closely spaced aligned craters, the Nejapa and Ticomo maars are both composed of a chain of several connected depressions (Avellan et al., 2012). The Twin Lakes cluster in Oregon, USA occurs as a closely spaced set of four aligned craters parallel to the Cascade Volcanic arc, where the compound North Twin Lake is composed of two connected depressions and sits <100 m north of the South Twin Lake crater rim (Fig. 6a). Although not suitable for the database because of truncation by the Miyakejima caldera, Suona crater Japan is one of several overlapping maar craters, separated by septa that form a chain (Fig. 6b). There are also much smaller diameter crater chains associated with average sized maars, such as Ubehebe Crater in California USA that has the prominent ~800 m Ubehebe crater, the Little Hebe complex of overlapping phreatomagmatic and magmatic vents to the south, plus a much smaller related chain of explosively excavated craters to the west (Fierstein and Hildreth, 2017; Fig. 6d). This resembles the Red Hill maar that has a disconnected chain of three craters to the south (Chamberlin et al., 1994; Fig. 6c). The Nejapa, Twin Lake, and Suona craters all occur in complex volcanic fields, while the smaller chains at Ubehebe and Red crater occur in relative isolation. Although temporal data is not available for all of these examples, the Nejapa-Miraflores maars and Ubehebe indicate that the craters were not formed simultaneously along a single fissure, and were the result of lateral migration of explosion locations.. Subsurface explosions that occur in different lateral positions but have overlapping explosion footprints produce circular to compound shapes (Valentine et al., 2015a) and are likely to have complex tephra rings. When explosions are spaced further apart, they can form a linked chain of craters (Valentine et al., 2015a). Additionally, the preservation of discrete craters in a chain suggests there has been little to no syn-eruptive collapse of the crater rim, preserving a more complete record of ejecta.

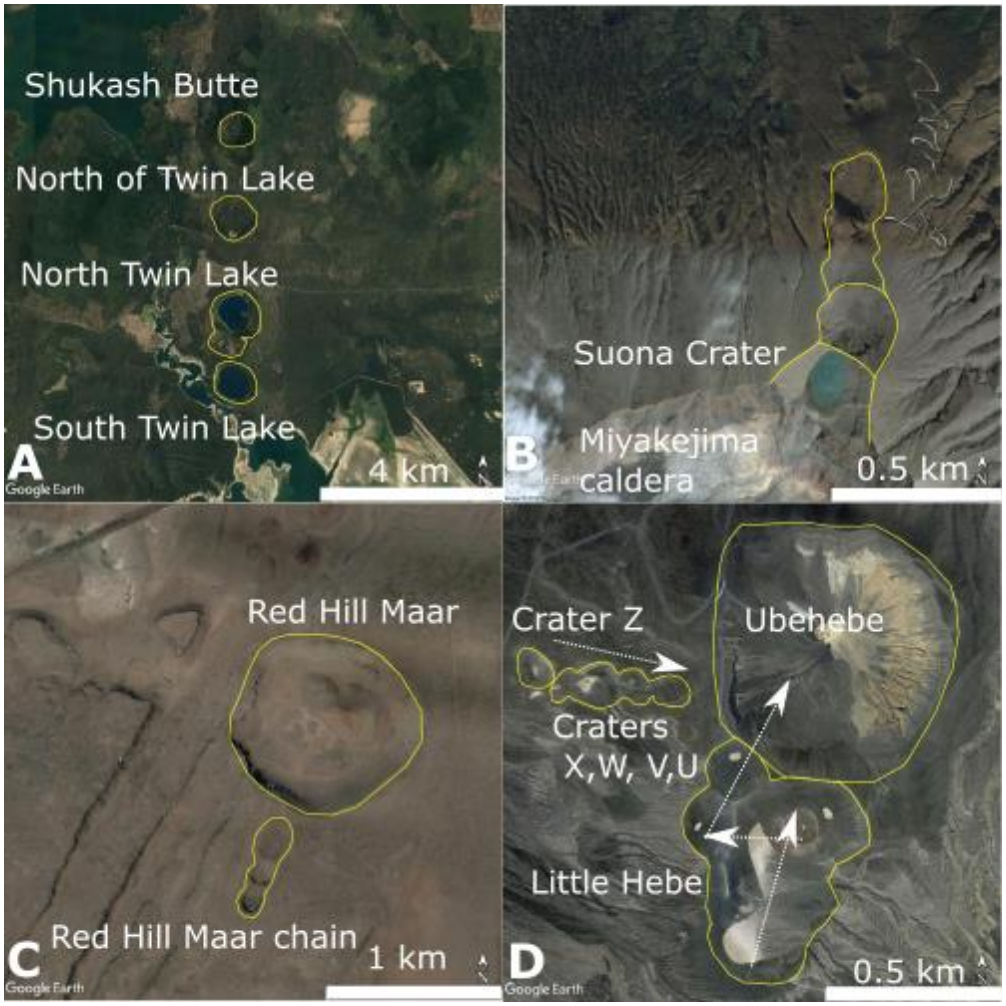

Figure 6 Examples of closely spaced or chains of maar craters mentioned in the text, not exhaustive of the database. A) Twin Lakes Oregon, USA; B) Suona crater (not included in database) and associated crater chain on Miyakejima volcano Japan; C) Red Hill Maar and chain, US; D) Ubehebe Crater, USA. White arrows represent general direction of vent locations from Fierstein and Hildreth (2017) where the final state of the eruption was from the main Ubehebe Crater. Images from Google Earth.

Maar-dominated volcanic fields

While maars are a common in both complex and small volume volcano fields, they typically make up a small percentage of the volcanic landforms in a given field. In large fields of small volcanoes (monogenetic fields) maars typically represent a few percent of the total vent population, for example the Newer Volcanic Province has 10% phreatomagmatic constructs of 416 with only 21 being strictly maars (Boyce, 2013) and the Pinacate Field in Mexico has 2% phreatomagmatic constructs out of >400 vents (Gutmann, 2002). In complex volcanic fields, maars can represent a larger percentage of the vents, but only a small volume of erupted material. In the Lamongan Volcanic field in Indonesia maars make up 30% of the preserved vents, but they are scattered around the base of a 1631 m tall Lamongan stratovolcano (Carn, 2000). The San Pablo Volcanic field contains at least 12 maars and sits in the Macolod Corridor in the Philippines nestled between Taal Caldera and several stratovolcanoes as well as dozens of scoria cones (Ku et al., 2009). There are, however, a few volcanic fields that are dominated by, or wholly composed of maar craters. The craters within these volcanic fields are frequently remote and poorly studied, and thus not all have representative craters in of the MaarVLS database. Along the East African Rift Katwe-Kikorongo near Lake Edward and Kyatwa/Ndale in Uganda, as well as the Bilate River Field in Ethiopia are composed almost entirely of maar craters. Other fields in the rift like Fort Portal and Bunyaruguru in Uganda are composed of maars, tuff rings, and lava flows (Kampunzu et al., 1998). Maar-only volcanic fields are also observed in back arc basins, such as Espenberg in Alaska and the Megata Volcanic Field in Japan, as well as one example in the compressional Qal'eh Hasan Ali in Iran. Several of these fields only contain a small number of vents (4-20; Table 4), unlike many small volume volcanic fields (monogenetic) that contain hundreds of vents. There are, however, Pleistocene (?) examples of volcanic fields in Tanzania near Mt. Hanang that contain > 100 phreatomagmatic vents (Delcamp et al., 2017). These fields have a diversity of tectonic setting, environment (permafrost, equatorial, arid), and spacing and shape of craters. With the exception of the Qal'eh Ali field in Iran (Milton, 1977), all of these other fields occur in extensional settings with a range of climates. This strongly suggests that while the availability of water is significant, the tectonic setting and the subsurface structure are critical to the conditions leading to maar-forming eruptions.

5.0 Evidence for lateral migration from maar crater size and shape

Planform crater growth is a result of excavation and subsidence by subsurface explosions, and collapse of the crater rim (Valentine and White, 2012; White and Ross, 2011). Analog experiments using buried chemical explosives indicate that the diameter of a crater with a laterally fixed blast location does not grow infinitely (Sonder et al., 2015), suggesting that for very large craters, and complicated crater shapes, lateral migration of the explosion locus is necessary and common (Valentine et al., 2015a). The range of expected phreatomagmatic explosion energies has been estimated from the volume of intrusions observed in eroded volcanic centers (Valentine et al., 2014) and the volume of individual beds in tephra rings (Graettinger and Valentine, 2017). Based on these energies and the observation of asymptotic growth of experimental craters (Sonder et al., 2015) the largest diameter of a single phreatomagmatic explosion in optimal conditions at the largest estimated natural energy (10^{13} J) would be 350 m in diameter. Experimental craters were observed to grow by ~60% in experimental settings with repeated optimal explosions and associated collapse. An ideal crater produced by tens of explosions without lateral migration could likely reach 560 m in diameter. Assuming this value is conservative, attempting to account for crater growth by post-eruption collapse, a crater of 700 m diameter falls in the 35th percentile of the MaarVLS database. Energy transfer in phreatomagmatic explosions is inefficient (Wohletz, 1986; Büttner and Zimanowski, 1998), meaning that these values are more likely to overestimate crater size from an eruption without lateral migration. Therefore, large craters, even with circular morphologies, require lateral vent migration.

Field studies have identified evidence of lateral explosion migration in tephra rings surrounding maar craters and exhumed diatreme structures (Ort and Carrasco-Núñez, 2009;

van Otterloo et al., 2013; Jordan et al., 2013; López-Rojas and Carrasco-Núñez, 2015; Valentine et al., 2015b). There are numerous influences on lateral migration of vents in growing maars such as the dimensions and geometry of the intrusions feeding the eruption, magma flux along that intrusion, the presence of pre-existing joints or faults, the distribution of water in the subsurface before and during the eruption, and other heterogeneities in the host rock.

Volcanic constructs in small volcanic fields frequently show an alignment with regional stress regimes and the orientation of feeder dikes (LeCorvec et al., 2013). The MaarVLS database demonstrates that a majority of maar craters are not ellipses that form along a linear feeder system. In other words the shapes reflect lateral migration in at least two directions and not simply along a single trend (Fig. 1e,f and Fig. 6d). Field observations of a maar-diatreme feeder system in Hopi Buttes Volcanic Field, USA revealed substantial geometric complexity of intrusions, including abundant sills that would make it difficult to produce simple elliptical craters (Muirhead et al., 2016). There are examples of maar craters that represent the simple scenario of eruption locations occurring along a tabular feeder dike, such as crater chains (Fig. 6), but they only represent a portion of the global maar population.

Several stratigraphic studies of phreatomagmatic eruptive centers have been used to reconstruct the relative timing and position of explosive vents within a maar to reveal that the migration of explosion locations did not progress along a simple line. Jordan et al. (2013) reconstructed a triangular distribution of vent positions that were occupied at multiple times during the eruption of Purrumbete maar in Australia. Fierstein and Hildreth (2017) demonstrated that the vent locations at Ubehebe Craters migrated in a zigzagging pattern that ultimately produced two intersecting linear trends of craters (Fig. 6). Historic observations of Ukinrek maar, and stratigraphic studies of multiple maars reflect that simultaneous eruptions of multiple vents can further contribute to crater morphology (Self e al., 1980; Jordan et al., 2013; Amin and Valentine, 2017). These studies highlight that maar crater shapes record important elements of the eruption evolution, and that the subsurface process controlling explosion locations are complex. Additional stratigraphic studies and the integration of structural, hydrological, and morphometric data may be useful in determining the typical spacing distance for migrating explosion locations.

These morphological observations, in addition to a growing literature on field observations of diatreme and tephra ring structures, including the documentation of magmatic deposits at various times during eruptions, suggest that the production of explosions in not solely limited by water availability rather the geometry of the plumbing system, magmatic flux, and the hydrological properties of the evolving diatreme. Further, the complex shapes of maar craters suggests that growing diatremes exert significant local control on the location of subsequent explosions resulting in large and compound crater shapes at the surface.

6.0 Conclusions

MaarVLS is the most comprehensive survey of planform maar morphometry to date and is a useful tool to investigate global trends in maar formation, highlighting the universal traits and unique subsets of these volcanoes. A typical maar crater is not circular, nor a simple ellipse, displaying elongation and large-scale deviations in the curvature of the crater rim with most crater sizes between 600 and 1000 m. Volcanic fields containing maars have a range of crater sizes and shapes where the largest maar crater is commonly less than twice of the size of the smallest maar. Magma composition and occurrence of multiple co-located eruptions through time do not seem to produce diagnostic crater sizes or shapes.

The MaarVLS database highlights the importance of lateral growth of craters in more than one direction supporting field-based observations that lateral explosion location is common and fundamental to the evolution of maar-forming eruptions. Additional work to relate shape with host rock properties, regional faults and local hydrology is planned to further isolate the influences on this lateral crater growth. Exceptional populations of large size craters, maar-dominated volcanic fields, and crater chains warrant further study as they have the potential to provide unique insight into the role of regional structures, ground ice, lateral migration, and co-located eruptions on the role of maar formation. Future comparison of this morphometric database with similar datasets for other negative landforms on Earth and Mars should lead to the remote identification of these volcanic features on both planetary surfaces.

7.0 Acknowledgments

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