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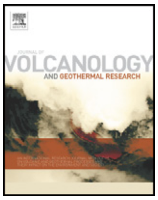

Scaling laws of the size-distribution of monogenetic volcanoes within the Michoacán-Guanajuato Volcanic Field (Mexico)

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ABSTRACT

The Michoacán-Guanajuato Volcanic Field displays about 1040 monogenetic volcanoes mainly composed of basaltic cinder cones. This monogenetic volcanic field is the consequence of a dextral transtensive tectonic regime within the Transmexican Volcanic Belt (TMVB), the largest intra continental volcanic arc around the world, related to the subduction of the Rivera and Cocos plates underneath the North American Plate. We performed a statistical analysis for the size-distribution of the basal diameter (Wco) for cinder cones. Dataset used here was compiled by Hasenaka and Carmichael (1985). Monogenetic volcanoes obey a power-law very similar to the Gutenberg–Richter law for earthquakes, with respect to their size-distribution: $\log_{10}(N >= Wco) = \alpha - \beta \log_{10}(Wco)$, with $\beta = 5.01$ and $\alpha = 2.98$. Therefore, the monogenetic volcanoes exhibit a (Wco) size-distribution empirical power-law, suggesting a self-organized criticality phenomenon.

1. Introduction

A monogenetic volcano (hereafter m-volcano) is the result of one single (or very few) magmatic pulse(s). The duration of the volcanic activity lasts from hours to years, generating an m-volcano, built up from the pyroclastic accumulation during the eruption, and a lava flow. In all the cases, the final volcanic edifice has a similar shape, which shows a simple truncated cone with generally a bowl-shaped crater at its top (MacDonald, 1972). Most of them are basaltic and/or andesitic cinder/scoria cones. Monogenetic vents can be very different depending on the water interaction with the magma while rising towards the surface. They can evolve from cinder cones (small interaction with water), usually characterised by high values of Hco (height of the m-volcano) to tuff ring (more water interaction and smaller values of Hco) and maar, high-explosive eruption due to the interaction of the magma with shallow lakes or aquifers, generating landscapes with crater lakes.

The basal diameters (Wco) of the world-wide monogenetic edifices range between 250 and 3000 m (Wood, 1979, 1980a). Simple linear relationships done on average values of different morphometric parameters of m-volcanoes have been proposed by several authors: $Hco/Wco = 0.18$ or $Wcr/Wco = 0.4$, being Wcr the diameter of the crater of the cinder cone (e.g. Porter, 1972; Wood, 1980a,b; Dóniz et al., 2008). Spatter cones exhibit a value of $Wco < 0.1$ km and, in general, maar-type displays basal diameter laying between $0.7 < Wco < 0.8$ km.

Usually, the shape of the cone is roughly circular and symmetric although elongated and opened cones are observed and attributed to fissure control during the growing process of the m-volcano (Breed, 1964) and/or related to the direction of the wind during the eruption. The orientation of these elongated m-volcanoes, when not affected by the wind, may be an indicator of the orientation of the minimum horizontal shortening (strain) and the orientation of the stress tensor during the vent emplacement (Takada, 1994; Tibaldi, 1995; Alaniz-Álvarez et al., 1998; Mazzarini, 2004, 2007; Pérez-López et al., 2009; Paulsen and Wilson, 2010). The location of a monogenetic volcanic field is also related with the differential stress value and the magma rate, in opposition to the location of polygenetic stratovolcanoes (Fedotov, 1981).

Mazzarini (2004, 2007) has applied a cluster analysis between cinder cone centres by using the two-point correlation method in Ethiopia. From his analysis this author estimated the crustal thickness value of 28 km for this area. Furthermore, Mazzarini et al. (2010) estimated the crustal thickness for MGVF ranging between 30 and

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40 km (mean of 38 km) and 32 km for the Chichinautzin VF. They conclude that the self-similar clustering of basaltic vents could be used for crustal thickness estimation within extensional tectonic areas. The interval value for cluster power-law behaviour of basaltic vent distribution is (1.3, 38.1) km.

M-volcanoes may grow as parasite edifices associated with a larger stratovolcano (e.g. Kilauea MF) (Porter, 1972) or in monogenetic fields (MF) of tens to thousand edifices over areas of hundreds to thousands of square kilometers, including flat plateau areas that are cultivated, such as the Michoacán-Guanajuato VF (herein MGVF) (e.g. Hasenaka and Carmichael, 1985).

The age of the MGVF spans through the Quaternary in general, the oldest circular basal shaped m-volcano being of Plio-Quaternary age. Older edifices are eroded and the morphology changes abruptly (Wood, 1980b; Hooper and Sheridan, 1998; Németh and Cronin, 2007; Valentine et al., 2007). They are not considered in this study, even thought the linear relationships of their morphometric parameters do not vary significantly (Wood, 1980b; Hasenaka and Carmichael, 1985). The erosive features observed on scoria cones may be a tool for dating different edifices of a particular MF (Wood, 1980a). Many monogenetic fields exist around the world (parasite and plateau-type) independently of the tectonic conditions (extensive, compressive and strike-slip tectonic regimes).

In this study, we analyze the size-distribution of m-volcanoes using a power-law similar to the Gutenberg–Richter's one for the magnitude distribution of earthquakes (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944). An m-volcano can be considered as a point (located at X, Y) with several associated scalar parameters: (1) size of the apparent dome, (2) duration of the eruption, (3) volume extruded by the cone, (4) dominant rock-type and (5) date of eruption. For the analysis performed here, we use the size of the m-volcano defined by the basal diameter (Wco).

2. The Michoacán-Guanajuato Volcanic Field (MGVF)

The Michoacán-Guanajuato Volcanic Field (MGVF) is located at the central part of the Trans-Mexican Volcanic Belt (TMVB) (Fig. 1). This volcanic arc is related to the subduction of the Rivera and Cocos tectonic plates underneath the North America Plate. The middle geometrical axis of the TMVB does not trend with a direction parallel to the Middle American Trench (MAT), but trends with a NW–SE direction from the west Pacific margin to the central part of the TMVB (Morelia city), turning to E–W from Morelia to the East Atlantic coast of Mexico (close to Veracruz city), and showing a deviation of 15ºW from the MAT (Fig. 1). This orientation is related to the shape of the 100 km depth of the subducted plate (e.g. Pardo and Suárez, 1995; Alaniz-Álvarez et al., 1998; Márquez et al., 1999a; Ferrari, 2004).

The TMVB is trending E–W with different styles of volcanism from the Pacific west margin of Mexico to the Atlantic coast. The TMVB shows a complex spatial pattern of migrating mafic pulses from the Middle Miocene (11 Ma) to Pliocene (3.5 Ma) (Ferrari, 2004). The main eruptive style of the TMVB is bimodal, active polygenetic volcanoes building stratovolcanoes as Colima, Pico de Orizaba, Popocatépetl, etc., and Quaternary monogenetic fields mainly composed by cinder cones.

The TMVB is divided into three areas: (1) Occidental area, located westward to the Sierra Madre Occidental, and related with the Jalisco

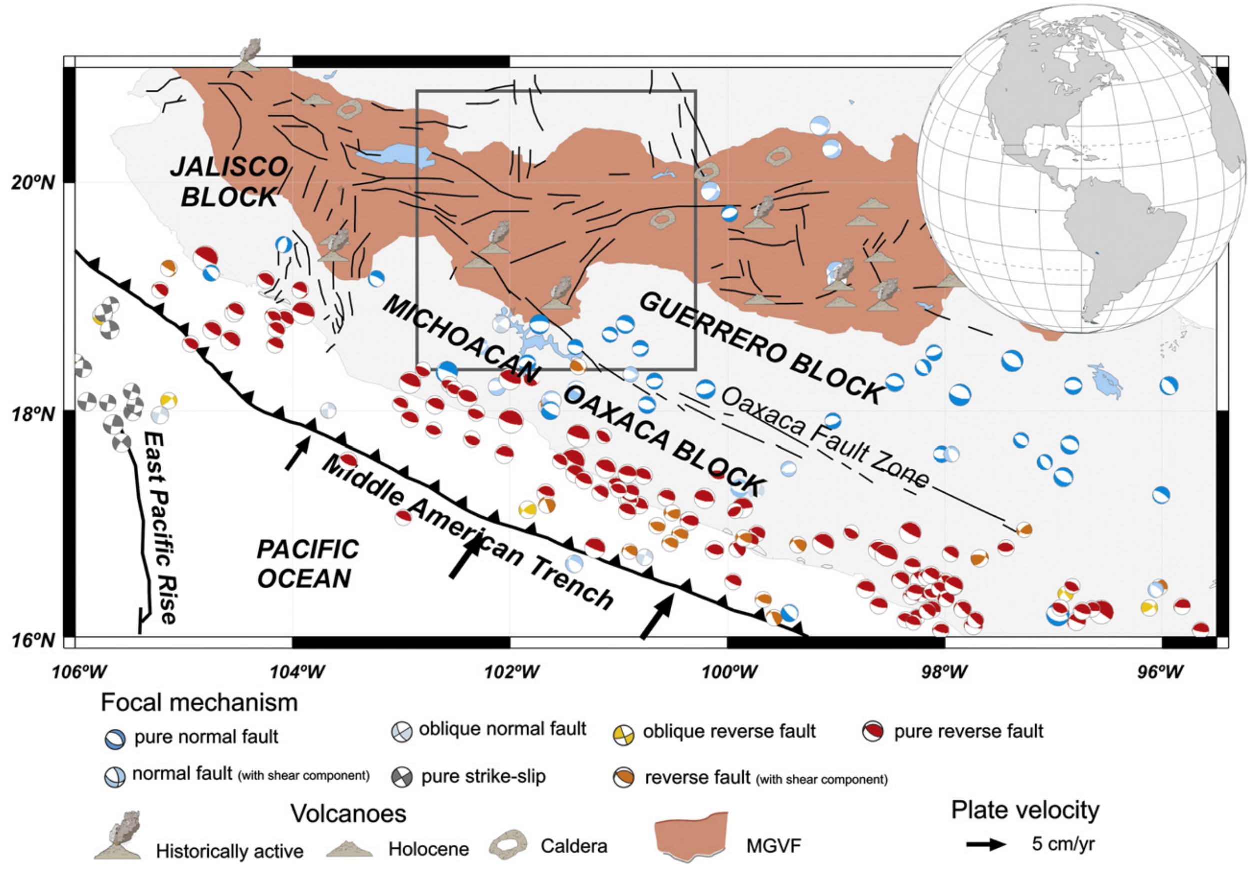

Fig. 1. Regional tectonic sketch of the Transmexican Volcanic Belt (TMVB) (solid grey colour) showing the convergence between the Rivera and Cocos plates underneath the North American Plate. Beach balls indicate focal mechanism solutions from the Harvard CMT Global catalogue (http://www.globalcmt.org). The Michoacán-Guanajuato Volcanic Field (MGVF) is indicated by a rectangle. Blue beach balls show extensional areas. Solid lines are active structures. After Pardo and Suárez (1995).

Table 1
Main geomorphic parameters of the MGVF from the Hasenaka and Carmichael (1985) database. Hco = height of the cinder cone, Wco basal diameter of the cone, Wcr = crater diameter, Volume, Hco/Wco, and Wcr/Wco and comparison with others monogenetic fields. VBMF = Valle de Bravo monogenetic field (Aguirre-Díaz et al., 2006), XAMF = Xalapa monogenetic field (Rodríguez et al., 2009) and SCHMF = Sierra de Chichinautzin monogenetic field (Martín del Pozzo, 1982; Márquez et al., 1999b).

MF name	Area (km^2)	Age	No. (m-vol)	Hco (km)			Wco			Wcr			Vol (km^3)			Hco/Wco			Wcr/Wco		
				Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
MGVF	4000	Late-Q	1040	0.6	0.05	0.089	3.2	0.03	0.76	2	0.02	0.25	0.65	0.001	0.033	3	0.007	0.11	4.33	0.03	0.29
VBMF	3703	40–10 ka	120																		
XAMF	2400	2–0.1 Ma	50			0.091			0.686			0.208			0.12						
SCHMF	952	Q	146	0.75	0.05		2	0.1													

Block, the Colima as the most relevant stratovolcano, (2) The Michoacán-Guanajuato Volcanic Field (MGVF) (Hasenaka and Carmichael, 1985; Hasenaka, 1994) related with the Michoacán Block, mainly composed by Quaternary monogenetic edifices (90%) of cinder cones, described in the following sections (Table 1), and (3) the Oriental Zone with the Xalapa Quaternary Volcanic Field (Table 1) (Rodríguez et al., 2009). The Xalapa volcanic Field has 50 m-volcanoes over 2400 km^2, with ages ranging between 2 and 0.1 Ma and averaged morphometric parameters of Hco = 91 m, Wco = 686 m, Wcr = 208 m and cone volume of 0.12 km^3 (Rodríguez et al., 2009). There are other monogenetic volcanic fields within the TMVB as the Valle de Bravo MF (Table 1) (Aguirre-Díaz et al., 2006), 120 cinder cones over 3703 km^2 and aged between 40 and 10 kyr and the Sierra de Chichinautzin MF (Table 1) (Martín del Pozzo, 1982; Márquez et al., 1999b), 220 scoria cones over 952 km^2 with 0.1 km < Wco < 2 km and 0.05 < Wcr < 0.75 km, for instance.

Connor (1990) has divided the TMVB in eight clusters by using a search radius of 16 km for a whole set of 1016 cinder cones. One of these clusters is the MGVF, although this author did not relate the vent alignment with the major strike-slip faults within the area, i.e. the Morelia–Acambay Quaternary fault system.

The MGVF represents a platform monogenetic field within the TMVB comprised by more than 1040 Late Quaternary monogenetic edifices (Fig. 2) with a cone density value of 2.5 cones/km^2 (Hasenaka and Carmichael, 1985) and a mean distance of 2 km each other (Fig. 3). These authors also pointed out that the estimated average of rate of eruption is 0.8 km^3/ka.

The youngest m-volcanoes of the MGVF are the Jorullo volcano (1759–1774) (Fig. 4) and Parícutin (*Parhíkutini*) (1949–1953) (Fig. 5). During the eruption of Paricutin, the basal diameter was reduced from 900 m to 600 m due to a fast submergence covering the base of the cone and Hco decreased from 210 m to 160 m (Wood, 1980a). Both display a quasi-perfect cinder cone defined by its morphometric parameters, the basal diameter (Wco), height of the cone (Hco) and the diameter of the crater rim (Wcr).

3. Scaling laws for size-distribution of m-volcanoes

We performed a scaling law with respect to Wco of the cinder cones of MGVF (Pérez-López et al., 2009), in a similar way as those done for earthquake sizes (magnitude), namely the Gutenberg and

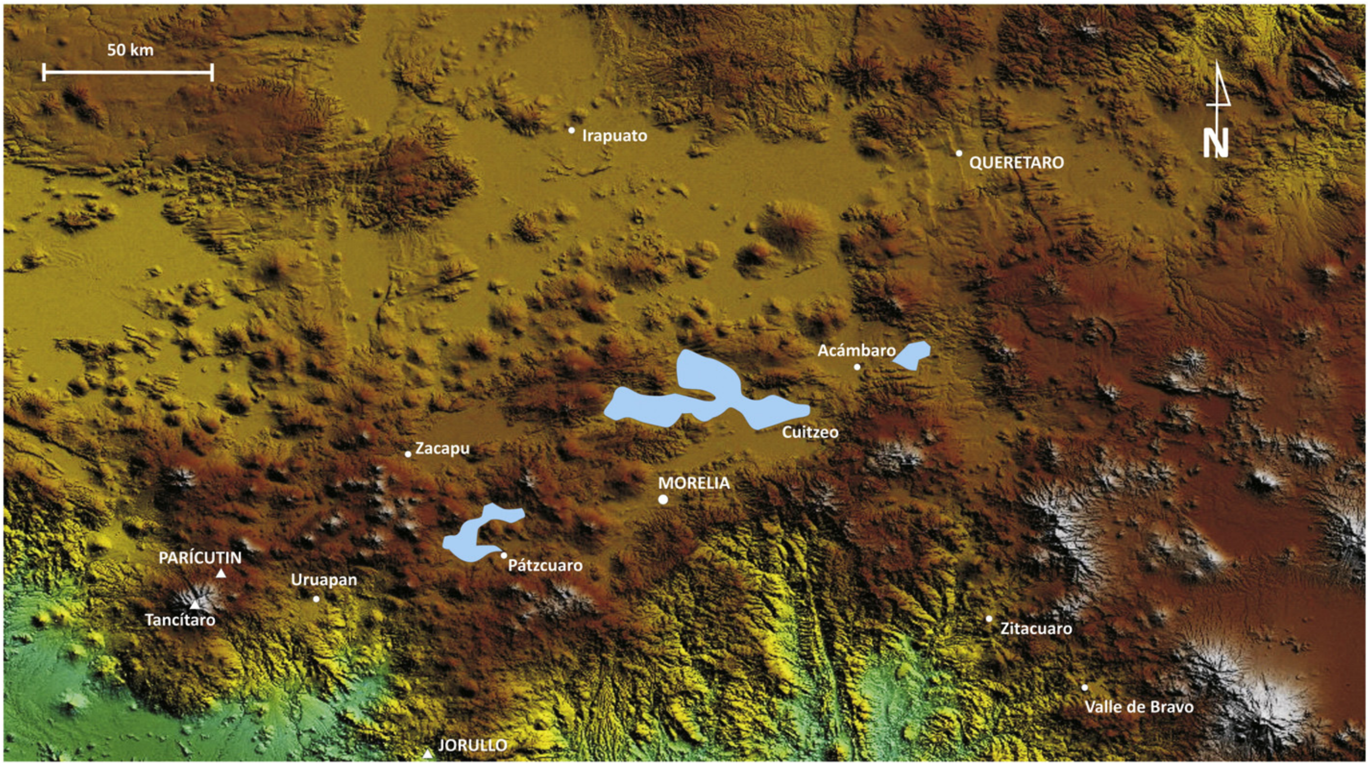

Fig. 2. Coloured shaded digital elevation model of the MGVF (30 × 30 m of pixel size). Two main qualitative monogenetic alignments can be interpreted from cone topographic features, NE–SW and NNW–SSW respectively.

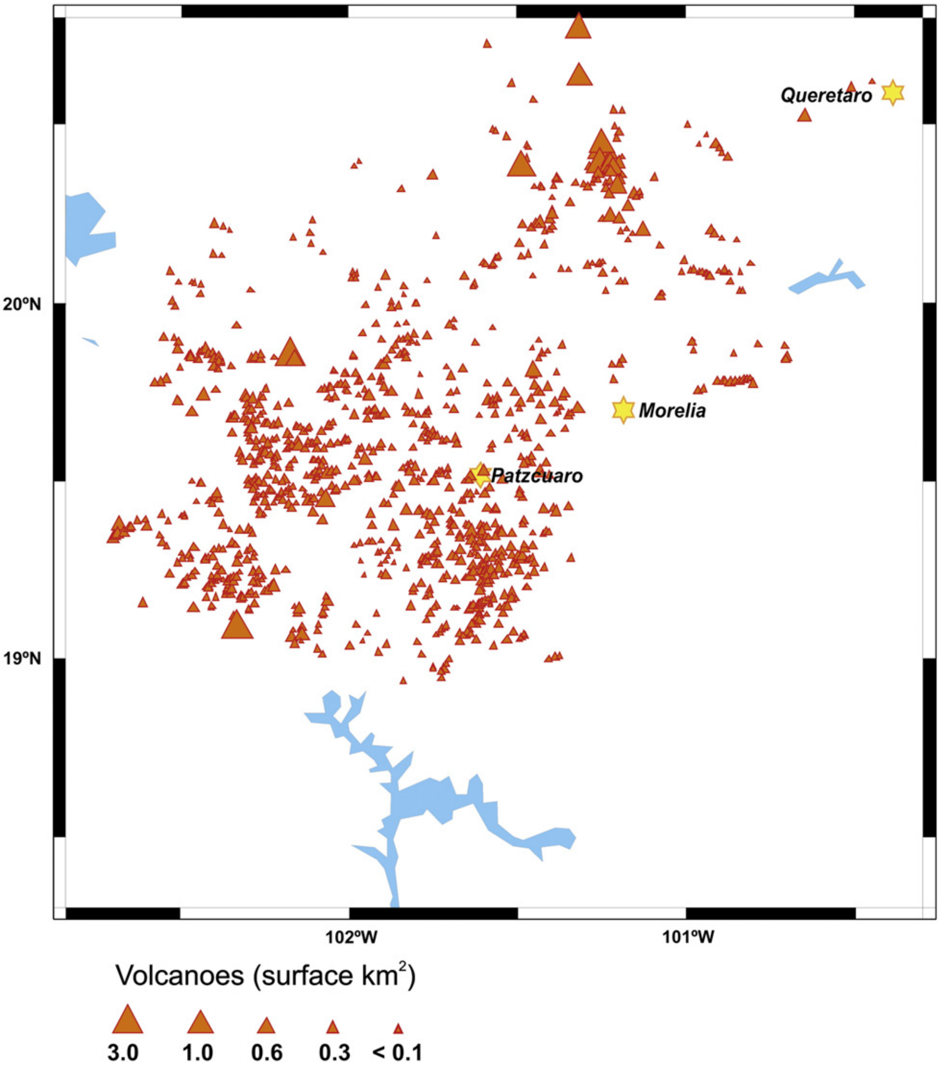

Fig. 3. Spatial distribution of m-volcanoes within the MGVF, circles size-weighed by the basal area of the cinder cone (Wco). Blue colour indicates lakes and stars the main cities within the area.

Richter law (GR) (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944).

3.1. MGVF database description

Most of the MGVF cinder cones are spatially distributed across a flat area and have been compiled by Hasenaka and Carmichael (1985) and revisited by Hasenaka (1994) in a database of 1042 cinder cones. Both authors estimated morphometric parameters such as Wco, Wcr and Hco basically from two sources: (1) 1:50,000 scale topographic maps from the INEGI (*Instituto Nacional de Estadística y Geografía Mexicano*), comprising the series E13B, E14A and F14C, which include the area of Michoacán and Guanajuato. The contour interval for these maps is 20 m. The resolution of these maps is 50 m, lesser than the minimum Wco value (200 m). (2) Field work to take measures of petrology and morphometric parameters for minor cones.

In consequence, the assumed error for the morphometric parameters measured by Hasenaka and Carmichael (1985) is not relevant for our analysis taking in mind that the lowest Wco value is 200 m.

3.2. Power-law distribution of Wco

We calculate the slope (called hereafter β-value) of the number of cones with a basal diameter greater than Wco in a similar way as it is done for the GR law. As far as the GR law is a log-normal law, its slope (i.e. the b-value) cannot be estimated by a mean square technique but with the maximum likelihood technique as proposed by Aki (1965) and Utsu (1966):

$$b = -\log_{10}(e) / (<M> - M_{min}]) \qquad (1)$$

Where <M> is the mean value of magnitudes for the earthquakes population, M_{min} is the minimum value of the fitted curve. The uncertainty for this estimation is (Aki, 1965):

$$\sigma = b^{*}1.96 / [(N[M_{min}])]^{0.5} \qquad (2)$$

Where $N[M_{min}]$ is the number of events of magnitude greater than M_{min}, with 95% of confidence.

The Wco threshold for the estimation of the β-value is 1.33 km for 954 Wco>0 (Hasenaka and Carmichael, 1985; Hasenaka, 1994) (Fig. 6A). Fig. 6B displays a power-law for the size-distribution of monogenetic cinder cones, following the equation:

$$\log_{10}[N \geq Wco] = \alpha - \beta \ \log_{10}[Wco] \qquad (3)$$

Where N is the number of cinder cones with diameter ≥Wco, α is a value depending on the size of the region of study and β -value is a

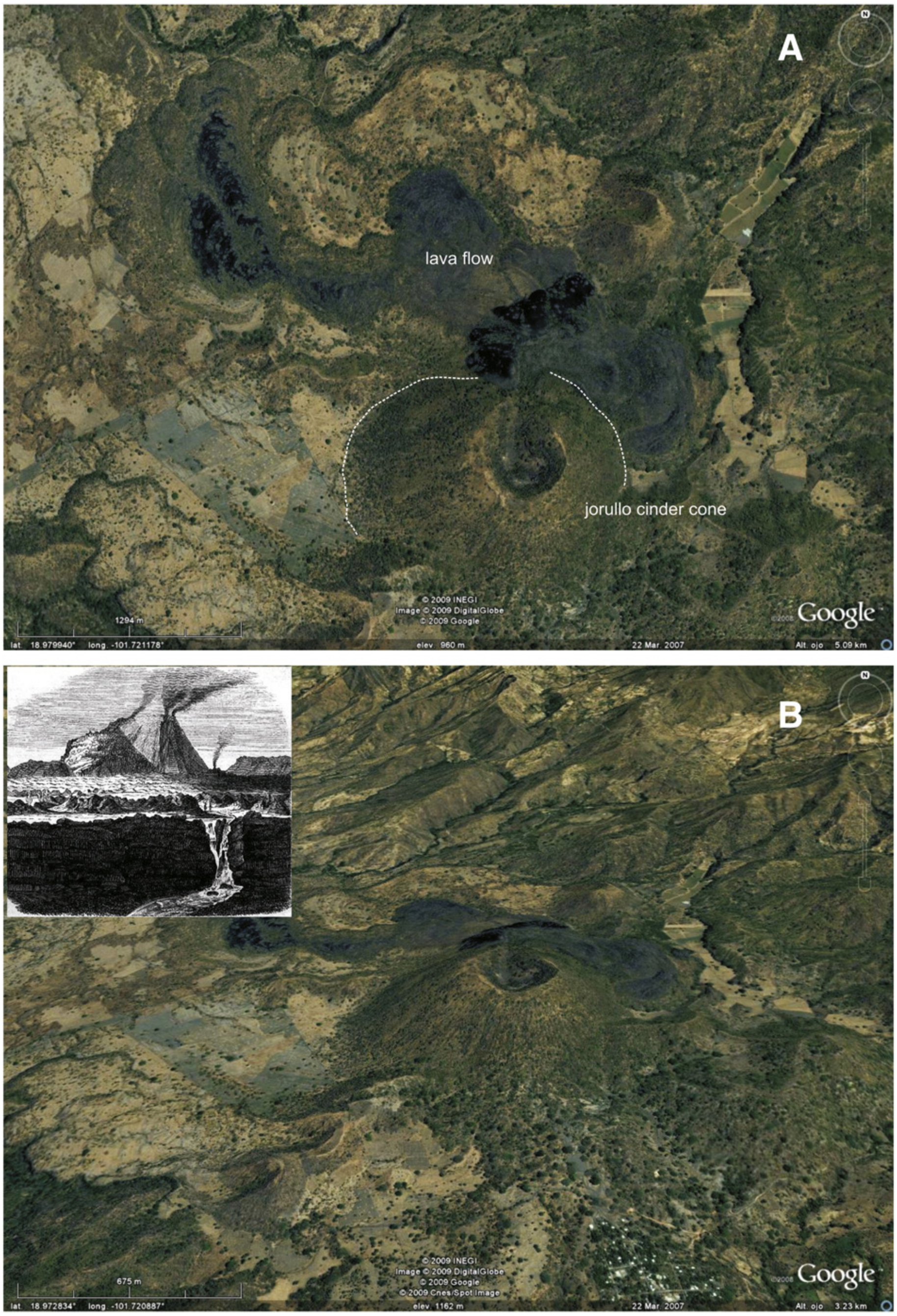

Fig. 4. Satellite image of the Jorullo volcano, a cinder cone was born in September, 29th in 1759 and died in 1774. During this time, gully incision and vegetation colonization were evolved.

constant. We have obtained a β-value of 5.02 ± 0.16 for the MGVF, with $\alpha = 2.9841$ for a total population for 954 cinder cones.

The threshold for the estimation of the β-value is related to the completeness of the catalogue, which can be estimated plotting the non-cumulative plot. As far as the number of small cones must increase, the threshold corresponds to the part for which the number of small cones started to decrease. In this curve, the threshold is 0.7 (Fig. 6). The error was estimated from Eq. (2) (Aki, 1965; Utsu, 1966).

4. Discussion

4.1. Geomorphic constraints for m-volcanoes

Thouret (1999) distinguished between short-term and log-term lived volcanic edifices, highlighting the relevance of the morphometric and comparative morphology for volcanic classifications. Independent of the tectonic frame, nature and size of the particles, depth of the magmatic chamber and eruptive rates, the morphology of m-volcanoes is dominated by these parameters (i.e. Porter, 1972; Wood, 1980a,b; Dóniz et al., 2008). The cone shape construction displays several phases during the eruption, being modified from the genesis to the post-eruption final stage. The stable aspects of the cone morphology are Hco, Wco and the slope, with a repose angle close to 30º (Wood, 1980a). However, as the cone does not include the volume of the associated lava flow and volatile ash, we cannot correlate the volume of the cone with the total energy released during the monogenetic eruption. Despite this, Wood (1980a) concluded that the cinder cones represent the most visible result of the monogenetic eruption and, consequently, the best parameter to quantify the phenomenon in spite of the cone represents a little fraction of the

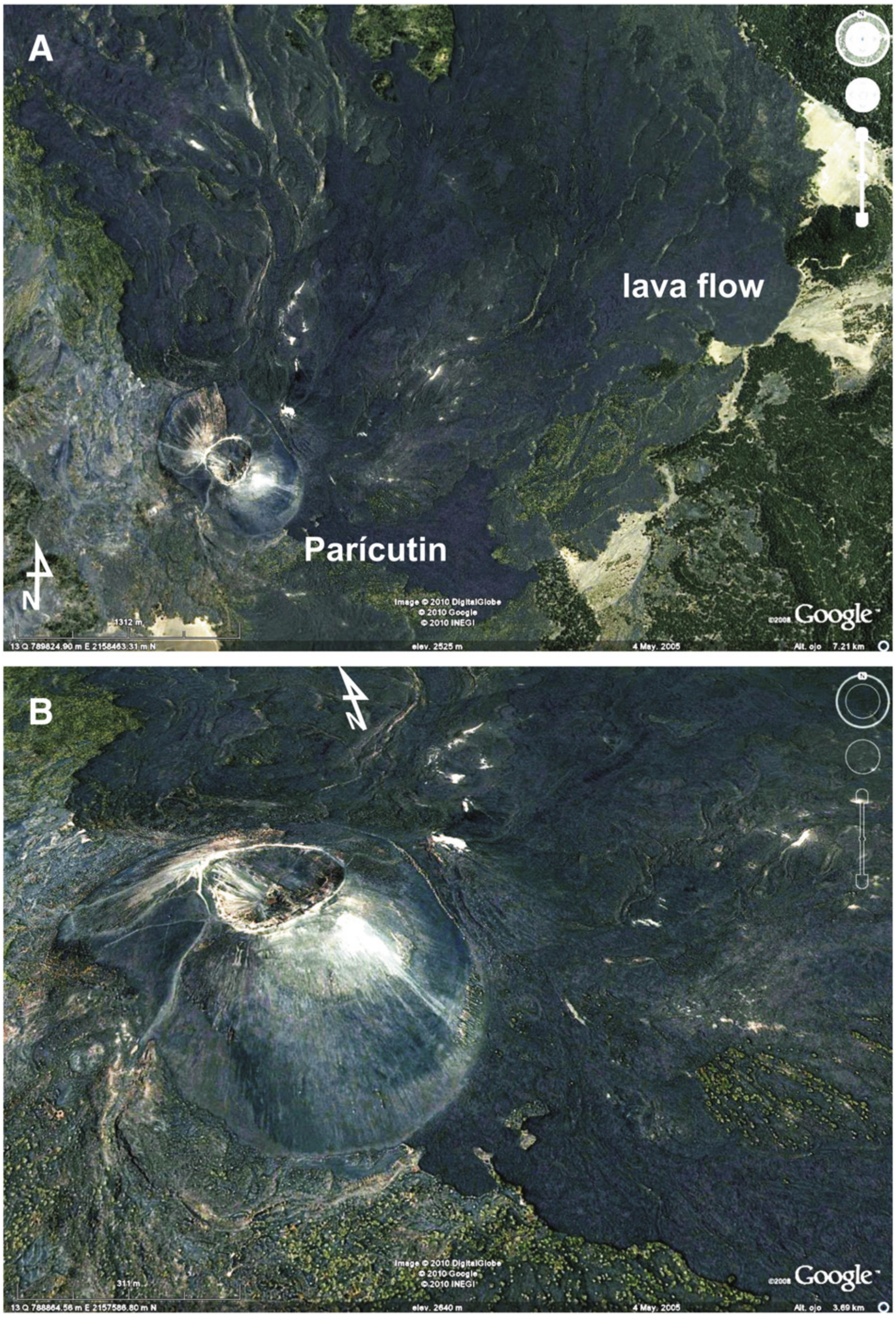

Fig. 5. Satellite image of the Parícutin volcano, which was born in 1943 and erupted till 1951 and detailed photo showing the geomorphology of the cinder cone. Note the incipient gully development in contrast with the Jorullo volcano (Fig. 4).

eruptive ash and lava output. Accordingly, the same cone could indicate eruptions with energy released differ in two orders of magnitude, for instance.

Moreover, Wood (1980b) stated that the cinder cone morphology may be strongly dependent of the cone age and, thus, statistical analysis performed to cinder cone dataset should be done with caution. However, the power-law for the Wco-distribution of the m-volcanoes of MGVF, suggests the shape-variations of the cones are small enough so that the log–log relation is not significantly affected by these fluctuations of shape. It is true that subsequent lava flows and later mass wasting from the cone flanks could modify the cone geometry, although the high quality fitting of the power-law for Wco-distribution suggests that statistical properties for morphometric values of cinder cones (Wco and Hco) have not varied significantly through the time (eruption and post-eruption phases) for m-volcanoes. Woods (1980b) pointed out that as lava covering and mass wasting are coeval, and the final equilibrated morphology reached by the m-volcano varies lesser than the 5%. This value is small enough so that is does not affect our log–log analysis which involves various orders of magnitude for Wco. At the same time, the erosion processes probably affected the whole m-volcano dataset in a homogeneous form, for example with similar steady-climate conditions to the whole area.

Consequently we assume that the Wco is the more stable parameter with respect to time, erosion and mass transport. This parameter changes in a similar way for all the m-volcanoes, during the eruption phase, the cone growth and the post-eruption erosion process.

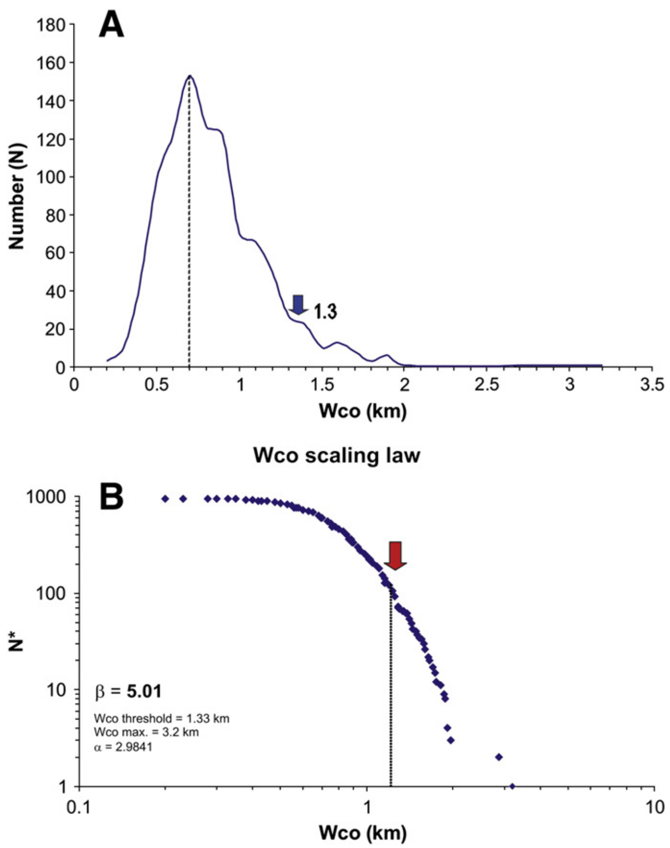

Fig. 6. Power-laws for the size-distribution of monogenetic volcanoes within the MGVF. (A) plot of the number of Wco values for the estimation of the Wco threshold (1.3), and (B) scaling law for Wco We estimate the β-parameter by using the maximum likelihood method (Aki, 1965). The threshold for the estimation of the β-value is related to the completeness of the catalogue that can be estimated plotting the non-cumulative plot. As far as the number of small cones must increase, the threshold corresponds to the part for which the number of small cones started to decrease. In this curve, the threshold is 0.7.

The MGVF displays cinder cones from the Upper Pliocene to the Present as the Jorullo and the Paricutín (Hasenaka and Carmichael, 1985). The climate associated both with the late-Neogene and Quaternary periods may be quite different within this area and, consequently, different rates of erosion may have affected the cones. However the law described here is a log relation for the Wco size-distribution, not sensitive to small variations due to erosion, so that the erosion does not affect the results in a significant way.

Favalli et al (2009) have discussed the role of the H/Wco rate to determine the age of cinder cones. The main arguments provided by these authors are (1) the method for calculating H and (2) lava burial of the cinder cone. MGVF displays cinder cones mainly distributed across a flat area and are not related with large slopes. The mean value of Hco/Wco is 0.18 for the MGVF dataset (Wood, 1980b), being the lower value 0.01 and the largest one 1.13. Fig. 7 shows the frequency distribution of Hco/Wco rate with the 90% ranging between 0.09 and 0.18. Therefore, the log–log relation for Wco is not sensitive to the Quaternary erosion rates within the studied area because of the variation for the Hco/Wco rate is lesser than two order of magnitude.

4.2. Interpretation of the β-value

The β-value expresses the relative number of small m-volcanoes with respect to large ones. As far as the β-value is an exponent of a power-law for the size-distribution of monogenetic vents (Eq. (3)), this size-distribution is scale-invariant. Scale invariant for size suggests fractality defined by the Wco of the cinder cones within the inner-outer cut-off interval.

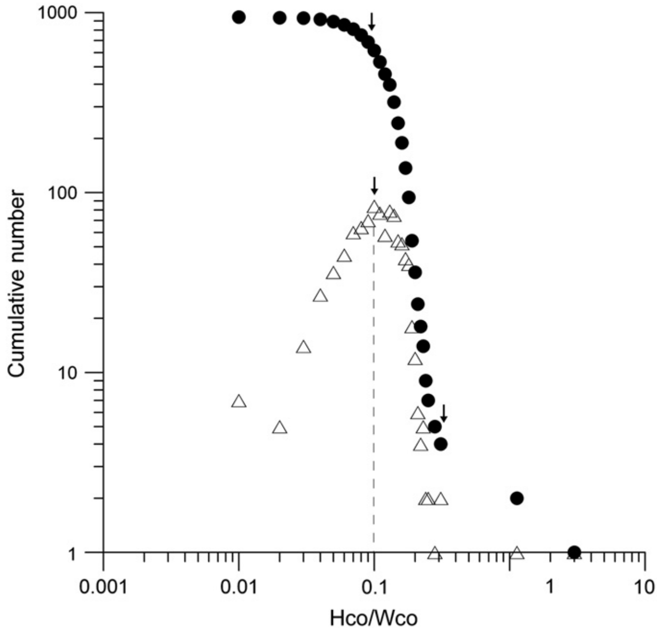

Fig. 7. Plot of Hco/Wco value for the MGVF (triangles). Note that 90% of volcanoes are located between 0.1 and 0.2 rates, in agreement with the main value of 0.18 found by Wood, 1980b. The accumulated plot (solid dots) exhibits a sharp change for values of 0.09 and 0.19. We have interpreted this interval as the interval of morphometric variation for m-volcanoes throughout time within the MGVF.

In the case of MGVF, the inner (0.7 km) and outer (3 km) cut-off for power-law behaviour of size-distribution for Wco (Fig. 6), could be related to different physical processes of magma ascension, in particular with the crustal thickness below the MGVF, because this value determines the Wco size during the monogenetic eruption (Fedotov, 1976; Wood, 1980b: Mazzarini et al., 2010). Other physical process could be the rate of magma rising towards the surface and/or the degree of fracturing of the crust, and may also depend on the stress/strain field (spatial and kinematics arrangements of fissures).

In continental arcs, the accepted thickness of the crust to produce magma reservoirs for basaltic cones is about 35 km and, consequently the larger basal diameter (Wco) for m-volcanoes may be related to this thickness (Fedotov, 1976; Wood, 1979, 1980b; Takada, 1994; Mazzarini, 2004, 2007; Mazzarini et al., 2010). Fedotov (1976) and Wood (1980b) pointed out a minimum value for Wco of 0.05 km and a maximum one of 2.5 km in relation with the continental averaged size for crustal thickness of 30–40 km. We found in this study that the outer cut-off for power-law plot of Wco size-distribution is 2 km (Fig. 6), which is within this range interval.

4.3. Monogenetic vent as a self-organized critical phenomenon (SOC): implications to volcanic hazard

The size-distribution of many natural phenomena is described by a power-law relation. This kind of distribution reveals that these phenomena are not due to hazard but are the results of physical processes that are self-organised critical (Bak et al., 1987).

SOC system is defined as a natural dynamical phenomenon with at least three degrees of freedom, which evolves from an initial state to a critical state defined by common features: (a) fractal geometry, (b) power-law behaviour and (c) variations in time that exhibit fractal noise (Bak et al., 1987). In the case of monogenetic vents, the SOC features are described both by a power-law for size-distribution (Kurokawa et al., 1995; Mazzarini and Armienti, 2001; Pérez-López et al., 2009) and by a fractal distribution of vents (Mazzarini et al., 2010).

5. Conclusions

The size-distribution of the basal diameter (Wco) for m-volcanoes of the Michoacán-Guanajuato Volcanic Field (MGVF) obeys a power-law similar to the Gutenberg and Richter's law for earthquakes:

$$\mathrm{Log}_{10}[\mathrm{N}(\mathrm{size} \geq \mathrm{Wco})] = \alpha - \beta \log_{10}[\mathrm{Wco}]$$

Where the β-value defines the rate of occurrence between small and large monogenetic volcanoes. The β-value for 954 cinder cones of the MGVF is $\beta = 5.02$ and $\alpha = 2.98$, with a Wco threshold ≥ 1.33 km and the β-value obtained using the maximum likelihood technique.

The power-law for m-volcanoes is interpreted as a self-organized criticality phenomenon, as Bak and Tang (1989) have suggested for earthquakes. This means that monogenetic fields are organized as complex phenomena in a critical equilibrium, as earthquakes do, being the monogenetic volcanoes of the MGVF distributed as a fractal in size.

This empirical power-law for m-volcanoes can be directly applied to future volcanic hazard assessment because of the β-parameter is directly related to monogenetic volcanic activity rates and the size-distribution does not occur randomly.

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