Method Article

A MATLAB App for calculating the age-dependent degree of erosion of monogenetic scoria cones from DEM data

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A B S T R A C T

We present a MATLAB App aimed to characterize the degree of erosion of monogenetic scoria cones from two independent sets of morphometric parameters. One quantifies the shape and size of undulations in DEM level contours through a novel parameter, the Average Erosion Index (AEI), using Elliptical Fourier Descriptors to calculate the wavelength spectra of undulations in selected contours over an ample range of resolutions of the database. The other is a more conventional set of parameters characterizing the vertical profiles of cones. This algorithm permits correcting those parameters for terrain inclination.

- These methods aim for a consistent assessment of the erosion-related relative ages of volcanoes in extensive monogenetic fields, from DEM data.
- The age-related degree of erosion is revealed by two main parameters: The Average Erosion Index (AEI), calculated from the Elliptic Fourier Descriptor spectrum of a scoria cone contour lines; and the aspect ratio of a scoria cone vertical profile, considering terrain inclinations, if it is assumed that all cones acquired the same morphology at the time of their formation eruptions.
- The Method provides erosion metrics from a sizable range of DEM resolutions. For age-related applications, it is recommended to use resolutions better than 12 m.

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| Slope and Aspect ratio method: | Favalli, M., K. Karatson, D., Mazzarini, F., Pareschi, M.T. and Boschi, E. (2009). Morphometry of scoria cones located on a volcano flank: a case study from Mt. Etna (Italy), based on high-resolution LiDAR data. Journal of Volcanology and Geothermal Research, 186, 320–330. https://doi.org/10.1016/j.jvolgeores.2009.07.011 |
| Bernis, K. and Ferencz, M. (2017). Morphometric analysis of scoria cones: the potential for inferring process from shape. Geol. Soc. Lond. Spec. Publ. 446, 17. https://doi.org/10.1144/SP446.9 |
| Zarazúa-Carbajal, M.C. and De la Cruz-Reyna, S. (2021). Digital Elevation Model resolution: Effects on the chronometry-oriented morphological analysis of scoria cones in the Sierra Chichinautzin, central Mexico. Geomorphology, 389, 107842. https://doi.org/10.1016/j.geomorph.2021.107842 |
| Resource availability: | MATLAB app to run in MATLAB 2020a: https://la.mathworks.com/matlabcentral/fileexchange/95398-erosionmetricsconicallandformssapp |

Background

Measuring erosion in landforms over extensive areas is feasible if a digital elevation model (DEM) of the terrain with an appropriate resolution is available. This type of analysis is of particular interest in monogenetic volcanic fields comprising hundreds or even thousands of scoria cones for its potential capabilities to estimate their relative ages. Each of such volcanoes erupts once producing different landforms. Among the common is the cinder or scoria cone, which are relatively small structures compared with polygenetic volcanoes. The conical shape of such structures is mostly controlled by the repose angle of granular material (scoria) which determines the cone slope at the time of the formation eruption. Indeed, the conical shape may be disrupted by different factors: basal terrain inclination, phreatomagmatic eruptions, eruption style shifts, tephr mantling, welding or agglutination, breaching, lava flows, among others. However, in treating the problem of measuring the degree of erosion, it is frequently assumed that all scoria cones within a cluster of monogenetic volcanoes had similar slope angles and aspect ratios at the time of their formation and that all have a similar response when exposed to the same erosive conditions. Such assumptions overlook important internal and external processes directly affecting the initial morphology of a cone and others affecting its response to erosive factors [10–12]. Nevertheless, if those assumptions can be sustained, a measure of the relative degradation state among the cones in a cluster can be obtained from the angle of the flank slopes, or the aspect ratio (the height of the cone divided by the basal diameter) [16,22,23].

Recently, a new approach to measure the relative degradation state of scoria cones employs a method based on the analysis of the Elliptical Fourier Descriptor (EFD) spectra of the landform closed contour lines. If the assumption that the landform surface was smooth at the time of its formation can be sustained, it follows that, as time passes, the formation of erosional rills and gullies may be measured in terms of the extent (wavelength) and depth (amplitude) of the undulations of the level contour lines, and that this information can be condensed in a single parameter named as the Average Erosion Index AEI [24].
Furthermore, under the assumption that the group of scoria cones was exposed to similar erosive conditions, an appraisal of the relative age among cones can be made using the available radiometric ages of the studied cones to establish functional relationships between the measured ages and the erosive condition \([2,8,9,15,23,24,26]\). Consequently, these methods may represent a helpful tool for the study of the volcanic field spatio-temporal evolution and its consequences on the volcanic risk.

Both approaches, vertical profile analysis, and contour line undulations have advantages and disadvantages, both assume that cones within a region have been exposed to similar erosive conditions, and their applicability may depend on the actual state of the scoria cones, the available radiometric age data, and the characteristics of the used DEM database.

**Average Erosion Index**

The age-dependent erosive condition of the landform is appraised with a single parameter, the Average Erosion Index (AEI), calculated from a DEM database using the level contour shape description attributes of the Elliptical Fourier Descriptors (EFD) \([13,17,24]\).

The (EFD) spectra of diverse shapes, including closed contour lines, have been used to characterize complex shapes in many geological, biological, paleontological, and anthropological studies (e.g., \([7,18,20,21]\)), even if their outlines are non-holomorphic, this is, with radii emanating from a centroid intersecting the outline in more than one point. Monogenetic scoria cones are landforms with smooth truncated cone shapes at the time of their formation. The age-dependent erosion is evidenced as changes in the volcano flank slopes and as height-dependent undulations of the cone surface. The information on the width and depth of those undulations is condensed in a single parameter: The AEI \([24]\).

The computation algorithm of the AEI develops in a series of steps \([24]\), as follows: 1) Identification of the level contours of the volcanic edifice. 2) Decomposition of each contour in its EFD using a specific type of Fourier analysis \([13,17]\). 3) For each contour computes a Similarity function \((S_{1k})\) measuring the overall likeness between the original and the kth-reconstructed EFD contour. Its value converges to zero as the contents of harmonics approach the Nyquist frequency \(\frac{1}{2} n\), where \(n\) is the DEM-resolution dependent number of sampled points of the contour, thus measuring to what extent each partially reconstructed contour approximates to the original sampled one. 4) Calculates an Erosion Spectrum \((D_{e})\) for each contour which measures the contribution of each harmonic \(k\) to the reconstruction of the “original contour”. 5) Computes for each contour the Erosion Index \(D\), which is an average of the erosion spectra, considering only harmonics running from that of the reference “original” contour to the highest, corresponding to the Nyquist harmonic. 6) Computes the AEI, averaging the Erosion indexes of all of the selected contours of a scoria cone. All of these procedures and parameters are described in detail in \([24]\). The App allows the implementation of all the necessary pre-processing for non-closed level contours, or to analyze specific angular regions of a scoria cone.

The App introduced here performs all the calculations needed to compute the single AEI parameter from a TIFF or GeoTIFF DEM of the volcanic edifice, in a sequential and sectorized form, allowing control of the calculations and the possibility to make modifications according to the interests of the user. It returns a single file with the AEI value of the analyzed cone, but it is intended to be an “open box” creating files and figures that can be accessed to further understanding how the results were obtained (Fig. 1).

**Volcanic cone slope and aspect ratio**

There are several different methods to characterize the morphometry of a scoria cone, which have evolved as the quality of the maps improved, and even more drastically with the development of the Digital Elevation Models \([6]\).

The aspect ratio is a frequently used morphometric parameter that can be strongly affected by factors highly sensitive to the DEM resolution, such as the criteria to define the limits of the base of a cone and the limits of the crater rim \([6]\), as well as the definitions used to estimate the basal diameter of a cone, or the cone height \([4]\).
Fig. 1. Overview of the algorithm code. Black lines denote MATLAB codes. Gray lines denote input and output information. Dotted lines show optional routines within the code.
In the methodology used in the App presented here, we implement an approach similar to that of Bemis and Ferencz [1], in which the cone dimensions are calculated from different elevation profiles, and then averaged. The sampling of different profiles provides more control on the characterization of cones with non-symmetric shapes affected by factors other than erosion, such as breached cones or crater rows. Additionally, we take into account the inclination of the underlying terrain to compute the height and basal diameter of the cone at each elevation profile obtained in the eight sampled cross-sections. This allows an equitable comparison of the aspect ratio \((AR)\) between cones emplaced in a horizontal terrain and those emplaced in an inclined one, as proposed and discussed by Favalli et al. [4].

This App is thus chiefly designed to compute the \(AEI\) index, and also can perform an analysis of the elevation profiles of a scoria cone, whose results generate a single Excel file containing the morphometric parameters obtained for 8 elevation profiles, 4 crossing the cones’ center and 4 crossing the crater’s center. Those profile parameters may be then used to estimate average parameters or managed according to the user interests.

Summarizing, the MATLAB scripts presented here can sample the DEM data, identify the volcanic structure, define the closed contours, select an option to calculate the EFD spectra at different heights of the cone, average them, and estimate the resulting \(AEI\). The scripts can also estimate the parameters that characterize the morphometry of the scoria cones’ elevation profiles and their dimensions.

The following table explains the different concepts, functions, and parameters used in the algorithms.

**Method details**

This App is composed of a succession of MATLAB functions. Each function automatically creates output files that are saved in a directory, which the user can check at any time to verify that all of the procedures are yielding results. The whole process is semi-automatic, but we recommend checking the outputs at each stage.

**How to run?**

Open a MATLAB Terminal and run the App “ErosionMetricsConicalLandforms”. A Window with five tabs will be displayed. The App has a modular design, so every tab can be run independently if the files required for that step already exist.

The required INPUT parameters are: The name of the DEM file containing any number of scoria cones, coordinates of the particular cone to be analyzed, name of that cone, horizontal resolution of the DEM, and name of the directory in which all created files will be saved.

The App contains five Tabs: A. DEM reading, B. Remove contour points, C. AnalysisEFD, D. AEI and E. Multiple Cones Analysis. The classification of level contours and the option to analyze the elevation profiles of the scoria cone are included in Tab A. Tabs B to D include all steps to obtain the Average Erosion Index, from the analysis of level contours of a scoria cone. Tab E allows computing the AEI of multiple scoria cones, if the required pre-processing is previously implemented.

In some steps, the analysis requires input from the user. How and where such input is required is explained in the following description for each tab.

**A. DEM reading Tab**

In this first tab, the App loads a DEM comprising one or any number of scoria cones in the file format TIFF or GeoTIFF. It requires the following input parameters: DEM file name, a directory name (in which the results of the analysis will be saved), the cone’s identification names, the DEM horizontal resolution in meters, and the Latitude and Longitude (in decimal degrees) of the center of the particular cone to be analyzed.

This App has been tested in DEMs with a Geographic Coordinate System.
This tab includes several buttons, some of them mandatory and others optional (Fig. 2). Each of them is described next.

A.1 LOAD DEM (mandatory)

Clicking this button reads the DEM from file ‘DEM File Name’, which should be a DEM in TIFF or GeoTIFF format.

A figure window will pop out showing a selected region of the DEM. If the displayed area does not cover the cone edifice, click on the ‘Change DEM Limits’ button. Otherwise, click on the Continue Button.

All text fields in this tab are mandatory. If one of them is empty, an error signal will be displayed.

NOTE: This code has been tested with DEMs having the reference matrix types ‘map.rasterref.GeographicCellsReference’ or ‘map.rasterref.MapCellsReference’. If while running the app an error concerning the type of reference matrix occurs, line 228 of the main App file (AppContoursMethodsX.mlapp) can be modified to fit the requirements of the Reference matrix in question.

A.2 Change DEM Limits (optional)

When this button is clicked, a figure displaying the DEM region will be activated. The user must first select with a mouse click a point in the lower left and then another in the upper right of the
After the two points are selected, press ENTER key on the keyboard.

A.3 Continue Button (Mandatory)

Once the limits of the region are defined, the program computes the contours of the DEM every 2 meters. Four figures containing the DEM gradient, the DEM 3-D contours, and a 3-D surface will be created, displayed, and saved (Fig. 3).

A.4 Lower resolution (optional)

When this button is pressed, the user has to specify the decrease factor (df=previous resolution/new resolution) in the correspondent field and then click the OK button (Fig. 4). This will create a subfolder “LResfdfl” in which the under-sampled DEM will be saved. If the check box “Use existing raster” is active, then the LOAD DEM step can be omitted, and the under-sampling will be performed in the DEM saved in the ‘Datos.mat’ file stored in the ‘directory’/’cone name’ folder.
Fig. 4. Decrease resolution option.
To perform the analysis in the new reduced-resolution DEM press the button 'Continue’ and everything will be saved in the “LResfd” folder.

A.5 Base Delimitation Button (Mandatory)

Base delimitation is made by visual inspection. The user selects points along the border of the base of the cone and the program defines a best-fitted ellipse based on the selected points. Delimiting the base of the cone should be performed by default on the contour image, but, if preferred, the gradient image may also be used selecting “Use Gradient image”.

When pressed, the Contour Image will be activated, the user should select at least 5 points delimiting the cone’s edifice. We suggest using 10-20 points. And then press the “ENTER” key on the keyboard. (Fig. 5a)

A.6 Rim Delimitation Button (Mandatory)

Rim delimitation is made by visual inspection. The user selects points along the border of the rim and the program defines a best-fitted ellipse based on the selected points.

Rim delimitation is performed by default on the 2-D contour image, if the gradient image is preferred, then select the “Use Gradient image” box.

When pressed, the Contour Image will be activated, the user should select at least 5 points delimiting the cone’s crater rim. If no crater rim is visible, then the selection should be a single point in the center of the cone or delimiting the highest contour. If the cone is breached, the selection should follow a circular or elliptical path from the part of the cone that is not breached. We suggest using 10-20 points. And then press the “ENTER” key on the keyboard Fig. 5b.

A.7 Export Contours Button (Mandatory)

This analysis identifies the contours belonging to the volcanic edifice on the image, based on the best-fitted ellipse [5] to the points delimiting the base of the cone (basal ellipse), and the best fit ellipse to points delimiting the crater rim (rim ellipse). Contours’ points located in the region delimited by the basal ellipse and the rim ellipse are classified as “Cone’s contours”. Contours’ points located within the rim ellipse are classified as “crater’s contours”. An identification number (ID) is assigned to each cone contour and crater contour. Lower ID values represent contours higher in elevation above mean sea level. These contours are saved in the folder “Salida2” to a .dat file, with names: ‘contourID-Cone.dat’ or ‘contourID-Crater.dat’.

After the classification is completed, the App displays two figures showing the rim ellipse and the crater ellipse on the left, and on the right figure the identified crater’s and cones’ contours (Fig. 6). All variables related to the cones DEM section is saved to a .mat file: ‘Datos.mat’, which will be used for the next steps of the analysis.

The properties of the basal ellipse and rim ellipse are also saved in “Sheet 2” of the Excel file ‘Morfometricos.xlsx’. The delimitation of the base of the cone, the crater rim, and the process to export contours can be repeated until the user approves the selection.

A.8 Elevation Profile Analysis button (Optional)

NOTE: The file Datos.mat must be created first, with the Export Contours Button, otherwise an error will occur. The name of the cone to be analyzed should be written in the Field: Name.

This button performs the analysis of eight elevation profiles, four crossing the center of the crater and four crossing the center of the base of the cone. The profiles are generated with an azimuthal separation of 45 degrees with respect to the orientation of the major axis of the base ellipse and with respect to the major axis of the rim ellipse.

One by one, the elevation profiles will be displayed, and the user is requested to select 5 points along the profile: left base limit (P1), right base limit (P2), left crater rim limit (P3), right crater limit (P4) and the lower point within the crater (P5). The order in which the points are selected is important. From these points the following parameters will be estimated: $\theta_{sus}$, $\theta_{cr}$, $Hc_{o1}$, $Hc_{o2}$.
Fig. 5. a) Base delimitation, b) Cones' rim delimitation.
Fig. 6. LEFT: Best fitted ellipses to crater rim (rim ellipse), and base of the cone (base ellipse). RIGHT: Red contours are cone’s contours; blue contours are crater contours.
$H_{co_{incl}}, H_{co_{2incl}}, \theta_1, \theta_2, \theta_{1_{incl}}, \theta_{2_{incl}}, W_{co}, W_{co_{incl}}, W_{cr}, W_{cr_{incl}}, D_{cr}, D_{cr_{incl}}, Z_1, Z_2, Z_{1_{incl}}, Z_{2_{incl}}, A_r, A_r_{1_{incl}}, A_r_{2_{incl}}, f_{incl}$. Fig. 7 shows a graphical representation of these parameters.

The obtained morphometric parameters for all profiles are saved in the “Sheet 3” of the Excel document: ‘Morfometricoxl.xlsx’. The supplementary File ‘MorphometricC.xlsx’ exemplifies the estimation of additional parameters obtained from these values, such as: Volume, or average values of the dimensions of the cone.

We recommend the elevation profile approach to compute morphometric values of breached or horseshoe shaped cones as this allows excluding the profiles passing through such regions from the averaging calculations.

**EFD Contour Analysis**

**B. REMOVE CONTOUR POINTS TAB**

This part of the analysis is not mandatory. Ideally shaped cones on non-inclined terrains, will normally not require this step.

It is designed for the user to select and remove the information of a contour shape evidently unrelated to erosional processes such as lava flows, flank collapses, mined sectors or farming regions.

Input parameters: directory name and cone's Name. Fig. 8.

*When is it necessary to remove points from contours?*

This step of the analysis is required when the contours include regions that are evidently affected by phenomena other than erosion processes. For example: open-crater regions of horseshoe shaped cones, mined regions, regions used for agriculture, or some points of the contours comprising lava flows Fig. 9.

**B.1 See Contours (optional)**

Displays Fig. 6, from which an assessment of which kind of point removal (if any) will be required.

**B.2. Cone region Panel (mandatory)**

Allows the selection of the contours from which points will be removed. “All cone” option considers all cone's contours. “Intermediate region” selects just the contours within the altitude interval: $[H_{min} + 0.25^\ast HT, H_{max} - 0.25^\ast HT]$, where $H_{min}$ is the minimum altitude of the cone, $H_{max}$ is the highest point in the cone, $HT$ is the net height of the cone in meters, i.e., $H_{max} - H_{min}$.

If a specific contour range is selected, the user is asked to fill in the contour ID of the contours to analyze (contour ID increases as Elevation of contour decreases). Contour ID according to elevation can be seen in file: 'XYSalida2.dat'

**B.2. Remove Points panel**

Contours can be edited in groups, or individually. We recommend simultaneous point removal for horseshoe shaped cones, or for cones with regions with human intervention (mining, agriculture, etc.) to be omitted from the analysis.

To select points, it is possible to use a ‘brush’ or a ‘lasso’ selection tool. This is done with the function selectdata.m [3].

**B.3 Remove Points Button (mandatory)**

When clicked, a Figure is displayed, showing the contours of the selected ‘cone region’, if the option ‘all contours’ is selected, or showing the first contour within the selected ‘cone region’. Fig. 10 shows examples of all possibilities.

If the ‘brush’ option is selected, the user should move the mouse cursor over the points to be removed while pressing the right mouse button. Points selected for deletion will be marked in red.
Fig. 7. Example of morphometric characterization of a scoria cone along an elevation profile.
If the ‘lasso’ option is selected, the point at which the mouse is clicked defines the anchor point of the lasso, to select points the mouse should be moved while pressing the right mouse button.

Once the mouse is released, all selected points are marked in red, and a pop-out window appears to confirm the point selection. The ‘Yes’ option accepts the selected points and proceeds to save the modified contours in a .dat file; ‘redo selection’ unselects the previously selected points and allows the user to select new points, ‘Cancel selection’ continuous with the program as no points would be removed, in such a case the modified ‘.dat’ file will contain exactly the same points as in the original.

For each modified contour a new file is created in the folder ‘Salida2’, with the name: ‘contourID_Mod.dat’.

It is very important for the correct execution of the following functions, to remove points as illustrated in Fig. 11.

C. EFD Analysis Tab

This step computes the elliptical Fourier descriptors of each of the contours belonging to a volcanic cone.
Fig. 9. Examples of regions requiring point removal. a) open-crater cone. b) landslide or lava flow, or other non-long-term erosive feature. c) part of an adjacent cone structure.
Fig. 10. a) options for selecting the vertical regions to be analyzed. b) All cone contours. c) intermediate region. d) specific contour range (contour 25 to 35 in this example)
Fig. 11. Example showing correct and incorrect point removal for the correct execution of the EFD analysis.
Input parameters are: Directory name and Cone Name (which should be the same as that used in the first Tab). If the analysis is performed for one cone sequentially, the check box “last used” can be selected Fig. 12.

C.1 Cone region selection

The user has to select the contours to be analyzed: all cone, intermediate region, or any specific region.

C.2 Run button (mandatory).

This button runs 'análisis_curvasN2B.m' file for all contours in the selected region. The analysis is performed in three steps:

1) Identifies if a Contour is closed, if not, it marks the points delimiting the “uncompleted regions” ($iP1$, $iP2$).
2) Completes the “uncompleted” contours with an ellipse centered in the contour’s centroid, with its major axis in a given direction and passing through delimiting points ($iP1$, $iP2$). See
Table 1
Principal parameters and definitions.

| Parameter | Description |
|-----------|-------------|
| $K$       | Denotes the number of Elliptical Fourier Descriptors (EFD) used to reconstruct a contour. It is the equivalent of a Fourier harmonic. |
| Original contour | The contour extracted from the DEM being analysed. |
| Reference contour | A smooth contour, reconstructed with the lowest $k$ harmonic having its best-fitted ellipse the same “flattening” value (1-ma/Ma) as the best-fitted ellipse to the original contour. Ma: major axis; ma: minor axis. |
| $< S_{1k} >$ | Similarity function. The average distance between the original contour and the contour reconstructed using up to $k$ EFD. |
| $D_k$ | Erosion Spectrum. Is the net contribution of each EFD harmonic $k$ to the full reconstruction of the original contour. |
| $D$ | Erosion index. The average value of the Erosion Spectrum, from the harmonic $k$ of the reference contour to the highest possible (Nyquist) $k$ which is determined by the sampling rate of a contour line. |
| AEI | Average Erosion Index. The average of the Erosion index of the selected contours of a scoria cone. |
| $Hc_{1o}$, $Hc_{2o}$ | Vertical distance between the base of the cone and the crater rim, for each cross-section of an elevation profile. |
| $\theta_1$, $\theta_2$ | Angle of inclination of each of the flanks of the cone for an elevation profile. |
| $Wc_{co}$ | Width (horizontal) of the base of the cone, from an elevation profile. |
| $Wc_{cr}$ | Width (horizontal) of the rim of the crater, from an elevation profile. |
| $Dc_{r}$ | Vertical distance between the deepest point within the crater and the line crossing the outline of the crater rim, from an elevation profile. |
| $\theta_{sus}$ | Angle of inclination of the terrain underlying the base of the cone, for an elevation profile. |
| $\theta_{cr}$ | Angle of inclination of the line crossing the points delimiting the crater rim outline for an elevation profile. |
| $Hc_{1incl}$, $Hc_{2incl}$ | Perpendicular distances between each of the two points delimiting the crater rim outline and the line joining the two points delimiting the base of the cone outline, for an elevation profile. |
| $Wc_{incl}$ | Width of the base of the cone outline for an elevation profile, considering the terrain inclination $\theta_{sus}$. |
| $\theta_{1incl}$, $\theta_{2incl}$ | Angles of inclination of each of the flanks of the cone for an elevation profile, with respect to the inclined base of the cone $Wc_{incl}$. |
| $Wc_{rincl}$ | Width of the base of the cone outline for an elevation profile, considering the terrain inclination $\theta_{sus}$. |
| $Dc_{rincl}$ | Perpendicular distances between the deepest point within the crater and the line crossing the two points delimiting the crater rim outline for an elevation profile. |
| $Z_1$, $Z_2$ | The trigonometric tangents of the angles $\theta_1$, $\theta_2$ for an elevation profile. |
| $Ar_1$, $Ar_2$ | The ratios $Hc_{1o}/Wc_{co}$ and $Hc_{2o}/Wc_{co}$ for an elevation profile. |
| $f$ | The ratio $Wc_{r}/Wc_{co}$ for an elevation profile. |
| $Z_{1incl}$, $Z_{2incl}$ | The trigonometric tangents of the angles $\theta_{1incl}$, $\theta_{2incl}$ for an elevation profile. |
| $Ar_{1incl}$, $Ar_{2incl}$ | The ratios $Hc_{1incl}/Wc_{co}$ and $Hc_{2incl}/Wc_{co}$ for an elevation profile. |
| $f_{incl}$ | The ratio $Wc_{r}^{incl}/Wc_{co}$ for an elevation profile. |

Zarazúa-Carbajal and De la Cruz Reyna [24]. Each completed contour is saved in a file with name: 'SalidaComp.ID.dat'.

3) Once the contour is completed, estimates the Elliptical Fourier Descriptors of the contour (using the algorithm of Kuhl and Giardina [13] programmed by David Thomas [19]).

This step creates several files, listed in supplementary Table 1.

Sometimes the automatic process to complete the contours may fail or requires improvement, as shown in Fig. 13. In such cases, the ‘Complete Single Contour’ option can be used.

C.3 Complete Single Contour (optional)

When pressed, this button calls another App called CompContours.mlapp, which allows to manually modify the parameters: Major axis ‘s angle of inclination (Phi) measured with respect to the horizontal axis and contour centroid, aiming to find a better elliptical transect passing through points ip1 and ip2 to close the contour. It also allows to remove points of the contours or edit the location of points ip1 and ip2 (Fig. 14).
Fig. 13. a) contour not requiring competition. b) One-sector completed contour c) Three- sectors completed contour. Example of completion needing improvement. d) unsuccessful completion process in one of the sectors. Green squares represent points from the original contour. Blue sectors represent completed regions. Gray and red stars represent the first and second limits of the completed sectors respectively ($iP1$ and $iP2$).
Fig. 14. The Single contour completion app. a) First b) After selection of “run out of Main App”. C) After OK is clicked, all options are displayed.
Here the user needs to insert the contour ID number, and in case the app is running independently of the Main App, the directory and the cone name should be specified.

After the contour ID number is specified, press ‘OK’. This displays a tab to control the inclination angle Phi of the major axis of the ellipse. The solution of the ellipse centered at the cone’s center and passing through $ip1$, and $ip2$ with the given $Phi$ is displayed in a figure. The user selects the best solution and then clicks “Complete Contour”. If no satisfactory solutions are found, then the user can change the centroid of the contour with the option “Change contour center”.

**C.3a Change Contour Center** *(optional)*

This allows the user to manually change the center (centroid) of the contour. To do so, the desired centroid point should be clicked with the mouse, and then press the key ‘ENTER’ on the keyboard.

Then, after entering the $Phi$ angle, a figure showing the completion ellipse option is displayed. Different completion ellipse options are displayed as the user rolls the “$Phi$” control.

**C.3b Complete Contour** *(mandatory)*

This button will proceed to complete the contour with the sector of the completion ellipses displayed in the figure. (see Fig. 15a and b). This step requires that the file '/analisisCurvasN2B.mat', generated in the EFDAAnalysis Tab, exists.

If the contour contains more than one sector to complete, after clicking the “Complete contour” button, the user should repeat the selection of $Phi$, and a new figure displaying the solutions passing through the new sector limits $ip1$ and $ip2$ (Fig. 15c). Again, if no satisfactory solutions are found, the user can change the contour centroid, or the region limits $ip1$ and $ip2$ if needed. Then, when a satisfactory solution is met, click the button “Complete contour” again. This will display the completed contour as shown in the example from Fig. 15d.

The whole process should be repeated until the contour is fully completed. Therefore, the ‘Complete Contour’ button has to be clicked as many times as the number of regions to complete displayed in App. Only when this number is reached, the updated data related to that contour, including the EFD decomposition, is saved.

**IMPORTANT:** The main file '/analisisCurvasN2B.mat' is updated with edited data for selected contour. A backup file of the last run is automatically created. ('/analisisCurvasN2Bbackup.mat'). To recover the last version previous to edition, just change the name of the backup file to '/analisisCurvasN2B.mat'.

The following extra options are also included:

**C.3c Edit region limits $ip1$ and $ip2$** *(optional)*

This option allows modifying the reference points $ip1$ and $ip2$. After clicked, the user must select with a mouse click the points that will be used as $ip1$ and $ip2$ (in that order) and then press the key “ENTER”. As a guide, small legends ‘1’ and ‘2’ are displayed in the figure to show which side should be clicked first.

**C.3d. Edit number of regions** *(optional)*

This option allows modifying the number of regions to complete. Click on the “Edit number of regions” button located inside the “OTHER OPTIONS” panel. This will display an editable field and an “OK” button. Insert the desired number of regions in the edit field and then press “OK”.

The current figure will become editable. Proceed to click with the mouse in the points delimiting each of the regions. (2 points per region required) in the following order:

1 If the region limits are the first and last points of the contour, select first the last point and then the first point.
2 Otherwise, select the points in the opposite direction of the point-id increment. As shown in Fig. 16.

**C.3e Delete Points**

This option allows deleting points from the selected contour.
Fig. 15. Example of the single contour completion app applied on a contour with two open sectors to be completed. a) Completion of the first sector of a contour. Contour points are shown in black. The thin line represents the selected best-fitted ellipse with a specified center and major axis inclination $\Phi$ that crosses points $iP1$ and $iP2$. b) The same contour as in a) after the first sector was completed with a sector of the selected ellipse. c) Completion of the second sector of the contour. The contour points are shown in black. The thin line represents the selected best-fitted ellipse with a specified center and major axis inclination $\Phi$ that crosses points $iP1$ and $iP2$. d) Result after full completion of the contour. Original points are marked in green. Blue points show completed regions. The EFD analysis requires the completed ellipse. However, the AEI calculation only uses information from the green sectors.

When clicked, a plot of the editable contour will be displayed, the user is required to select with the “brush” the points to remove. After selection, the user must confirm the selection.

IMPORTANT: This does not overwrite ‘ContourMod.dat’, instead it creates ‘ContourMod2.dat’ which has priority over the other files.

As a second step, it is required that the user adds the number of regions to edit and their delimiting points, in the same way as required by the "Edit number of regions" option.

D. AEI TAB

This part of the analysis computes first the Similarity function and then the AEI. It requires the directory name and Cone name as input parameters (Fig. 17). Files created with previous steps (A-C) should exist, otherwise, an error will occur.

D.1 Similarity function Panel

To compute the Similarity function, the user has to select first the vertical region of the cone to analyze: all cone, intermediate region, or any specific contour range. The selected region must be the same or contained within the region selected in step C. Then click on “Run”.
Fig. 16. Example of how limit points for edited regions should be selected.
For each contour, a control graph showing the points of the contour that are considered for the Similarity function calculation (considered points) is created and saved. Also, the mat files containing the Similarity functions for each contour are saved. Fig. 18 shows an example of the considered points in a contour.

The “skip angular section” is an optional feature allowing to omit points of an angular range of the contour, from the calculations of the Similarity function. The angle range must be in degrees. The user can optionally add another identification name to save the files created after the elimination of the selected angular region.

D.2 AEI computation

This step computes the Average Erosion Index of the contours comprising the selected region of the landform. This requires the existence of files created in previous steps (A to D.1).

After the selection of the analysis region in the AEI estimation-Cone Region Panel (Fig. 17), the user has the option to include an extra identifier name that will be included in the output file’s
Fig. 18. Example of a control graph displaying a comparison between the closed contours rendered after a completion process (original completed) and the contour obtained using an inverse EFD transform, considering all harmonics up to the Nyquist harmonic (rec. contour), and in pink circles, the points belonging to the original contour selected for analysis. The expected output is that the EFD reconstructed contour and the original completed contour should coincide.
name. To proceed with the analysis, click on the “Compute AEI” button. This will perform a series of calculations: First, for each contour, within the selected region, the reference contour is identified, based on the characteristics of the best-fitted ellipses [5] to each of the reconstructed contours using up to $k$ harmonics of the EFD [24]. For each contour, a '.fig' file showing the Flattening function of the best-fitted ellipses as a function of $k$ is saved. Secondly, using the Similarity functions of each contour, the corresponding Erosion Spectrum $Dk$ is computed. A '.fig' file containing the Erosion Spectrum graph is saved. Finally, for each contour, the Erosion Index $D$ is computed. The AEI of the selected region is calculated, as the weighted average of the erosion index values of all contours within the selected region. A '.mat' and '.fig' files containing the $D$ value for each ID contour and the obtained AEI are created and saved. Fig. 19 shows an example of the figures, created for the estimation of the erosion index of a single contour. Fig. 20 shows an example of the AEI estimation for a group of contours.

Results are summarized in sheet number 4 from the file ‘Morfometricos.xls’.

Outliers identification

When the number of contours analyzed is greater than 30, a histogram of the $D$ value per contour is created. The data histogram is then fitted to a normal distribution. Outliers are those points with a $D$ value greater or lower than the mean value of the normal distribution +/- 2 standard deviations. The $D$ values, along with contours completeness information can help to identify possible reasons leading to an outlier $D$ value. If needed, corrections can be performed using the functions in this App, such as the “complete single contours” or “remove points”. The histograms are saved to a '.fig' file.

D.2a Edit AEI (optional)

This option is useful when the AEI has already been computed for each contour and the user wishes to obtain an additional AEI average on another region of the cone, or after contours with outlier $D$ values are identified.

Click the 'Edit AEI' box. Then, if desired, insert an identification name in the “extra name” field. If no “extra name” is given, the output files will overwrite the existent files. Finally, click the 'Edit AEI' button. This will launch a window containing a graph showing $D$ for that contour ID. Right-click with the mouse over the points to be removed, and then press ENTER. A new figure will be displayed and saved, as well as a '.mat' file containing the updated AEI value (Fig. 21).

The edited results are saved in an extra sheet from the file ‘Morfometricos.xls’.

D.2b Visualize Analyzed Contours (optional)

When clicked, this button creates a plot highlighting the contours, and contour sectors that were analyzed. This figure is automatically saved in '.fig' format Fig. 22.

E. Multiple Cones Analysis Tab

This tab is intended to speed up the analysis if multiple cones should be analyzed. It is required that the files created with the DEM Tab exist, and that point removal has been already implemented for each cone when needed Fig. 23.

Input Parameters: Name of the directory in which the required files are located (same as used in the previous tabs), name of file '.txt' containing the list of names of the cones to be analyzed. These names should be the same used as “Cone name” in the DEM reading tab. The .txt file should be placed in directory”.

E.1 LOAD BUTTON

Loads a list of names from the given '.txt' file. All names should be written without spaces in a column.
Fig. 19. Example of the calculations needed to compute the Erosion index $D$ of the contour in Fig. 18. a) Flattening function with a well-defined change point. b) Similarity function showing reference harmonic ($p_1$). c) Erosion spectrum of the region comprising harmonics greater than the reference harmonic. Inset shows the full Erosion Spectrum. d) Plot showing the identified reference contour, the reconstructed contour using just first harmonic ($k=1$) and the points of the contour considered to compute the Similarity function and Erosion Spectrum.
Fig. 20. Erosion index ($D$) for each contour in the analyzed region. Blue: $D$ value for all analyzed contours, red: $D$ value for contours selected for AEI estimation, (i.e. excluding contours with outlier $D$ values). Pink: weighted $D$ values of selected contours. Here, the $D$ values are multiplied by a weighting factor between 0 and 1 depending on the number of “completed” points in a contour. So contours with no completed sectors have weight 1, and a maximum contribution to the AEI.

To run this option, the files created with the DEM reading tab should exist. And all contours should be ready for analysis, that is, unwanted regions should have been already removed.

E.2 Extra Identifiers Panel (optional)

If the files to be analyzed have or require “extra names”, they can be included here. Notice that these extra names will be added to all cone names in the list.

- Extra Name: for files generated with AnalysisEFD.
- Extra Name B: for files generated in the Similarity function estimation.
- Extra Name C: for files generated in the AEI estimation.

E.3 Cone Region Panel

The user selects the vertical region of the cone for which the selected analysis will be performed.

E.4 RUN BUTTON

Executes each of the selected functions (Analysis EFD, Similarity function, AEI estimation, Visualize Analyzed Contour, or Final List) for the selected cone region.

Final List, reads results obtained with the AEI estimation step and creates a list with cone name, latitude, longitude, the resulting AEI and its standard deviation. This list is saved in the given directory, both in '.dat' and '.mat' files with name: “AnalisisAEIList”.

Method validation

The methods described above have been applied to DEM data in two research articles: Zarazúa-Carbajal and De la Cruz-Reyna [24] and Zarazúa-Carbajal and De la Cruz-Reyna [25]. In the former, we introduced the Average Erosion Index AEI, which is a new measure of the age-dependent degree
Fig. 21. a) When Edit AEI is selected, the user can introduce an Extra name for the file in which this will be saved (to avoid overwriting). b) Example of removing points from the example in Fig. 20.

of erosion in monogenetic volcanoes, requiring the assumptions that very young cones have smooth surfaces and that all cones within a region have been exposed to similar erosive conditions. Then, a novel morpho-chronometric relationship was established correlating published radiometric ages of scoria cones in the Sierra Chichinautzin volcanic field with AEI values calculated from two DEMs, a 5 m resolution airborne LIDAR DEM (INEGI, Mexico) and a 12 m resolution satellite radar mission (TanDEM DLR, Germany). This permitted to test the sensitivity of the methods to the DEM resolution, an analysis that rendered comparable results for both DEMs, opening the possibility to apply the methodology worldwide, in any volcanic field covered by satellite data with 12 m resolution or better.

In the second paper, we further discussed the effects of the DEM type and resolution on different morphometric parameters characterizing scoria cones of the Sierra Chichinautzin volcanic field, including the elevation profile analysis of their vertical cross-sections, and a more detailed analysis of the AEI level contour method. Both analyses were performed over a wider range of DEM resolutions, including the 5 m airborne LIDAR DEM (https://www.inegi.org.mx/), the 12 m TanDEM-X (TanDEM-X Science Serverdlr.de), and the 30-m ASTER GDEM-V3 [14]. We concluded that the morphometric characterizations of cones with volumes greater than 0.01km³ render similar results with different DEM databases provided their resolutions are better than 12 m. Regarding the age dependence of
Fig. 22. Example of visualization of the contours from Fig. 22. Analyzed contours are shown in black. All contours of the volcanic cone are marked in dark gray.
Fig. 23. The multiple cone analysis tab.

diverse scoria cone morphometric parameters, the AEI resulted to be a more sensitive age estimator than the aspect ratio of the vertical profiles. According to the results obtained from the SCMVF, while the AEI may be capable to resolve morpho-chronometric relative age differences of about 5 ka in cones in the age range 0-20 ka and about 15 ka in the range 20-230 ka, the Aspect ratio $Ar$ may only resolve age differences of about 40 ka of cones up to 230 ka. It is important to emphasize that these results are statistical trends obtained from a limited number of scoria cones in a single monogenetic field [25]. We expect that as the number of cones in different volcanic fields analyzed with these methods increases, the age resolution and the ranges of applicability will become better defined.

Conclusions

In this work, we present a MATLAB App and the related scripts required to execute all the steps of a new method designed to appraise the age-dependent degree of erosion in landforms with closed level contours, particularly in monogenetic volcanic cones, using encompassing DEM databases over a wide range of resolutions and data types. In particular, this method may be used to estimate relative ages of scoria cones in extensive monogenetic volcanic fields, determining
functional relationships between the radiometric ages of some sampled volcanoes and the Average Erosion Index. This parameter provides a measure of the age-dependent degree of erosion calculated through the Elliptic Fourier Descriptors analysis of the undulations in the closed level contours of the volcanic cones. Additionally, the App can also calculate the cone dimensions and other commonly used morphometric parameters related to the vertical cross-sectional shape of a cone from the DEM database.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi: 10.1016/j.mex.2021.101454.

References

[1] K. Bemis, M. Ferencz, Morphometric analysis of scoria cones: the potential for inferring process from shape, Geol. Soc. Lond. Spec. Publ. 446 (2017) 17, doi:10.1144/SP446.9.
[2] K. Bloomfield, A late quaternary monogenetic volcano field in central Mexico, Geol. Rundschau 6 (1975) 476–497.
[3] J. D’Errico, Graphical Data Selection Tool, MATLAB Central File Exchange, 2020 https://www.mathworks.com/MATLABcentral/fileexchange/13857-graphical-data-selection-tool Retrieved December 15, 2020.
[4] M. Favalli, D. Karatson, F. Mazzarini, M.T. Pareschi, E. Boschi, Morphometry of scoria cones located on a volcano flank: a case study from Mt. Etna (Italy), based on high-resolution LiDAR data, J. Volcanol. Geotherm. Res. 186 (2009) 320–330, doi:10.1016/j.jvolgeores.2009.07.011.
[5] O. Gal, fit_ellipse, MATLAB Central File Exchange, 2020 https://www.mathworks.com/MATLABcentral/fileexchange/3215-fit_ellipse Retrieved November 20, 2020.
[6] P. Grosse, B. van Wyk de Vries, P.A. Euillades, M. Kervyn, L.A. Petrinovic, Systematic morphometric characterization of volcanic edifices using digital elevation models, Geomorphology 136 (2012) 114–131, doi:10.1016/j.geomorph.2011.06.001.
[7] F. Guy, H.-T. Mackayo, A. Likus, P. Vignaud, M. Schmittbuhl, M. Brunet, Symphysial shape variation in extant and fossil hominoids, and the symphysial of Australopithecus bahrelghazali, J. Hum. Evol. 55 (2008) 37–47.
[8] D.M. Hooper, M.F. Sheridan, Computer-simulation models of scoria cone degradation, J. Volcanol. Geotherm. Res. 83 (1998) 241–267.
[9] M. Inbar, M. Gilichinsky, I. Melkekestsev, D. Melnikov, N. Zaretskaya, Morphometric and morphological development of Holocene cinder cones: a field and remote sensing study in the Tolbachik volcanic field, Kamchatka, J. Volcanol. Geotherm. Res. 201 (2011) 301–311, doi:10.1016/j.jvolgeores.2010.07.013.
[10] G. Kereszrti, G. Jordan, K. Németh, J. Dóniz-Páez, Syn-eruptive morphometric variability of monogenetic scoria cones, Bull. Volcanol. 74 (9) (2012) 2171–2185.
[11] M. Kervyn, G.G. Ernst, J.-C. Carracedo, P. Jacobs, Geomorphometric variability of “monogenetic” volcanic cones: evidence from Mauna Kea, Lanzarote and experimental cones, Geomorphology 136 (1) (2012) 59–75.
[12] G. Kereszrti, A. Geyer, J. Marti, K. Németh, F.J. Dóniz-Páez, Evaluation of morphometry-based dating of monogenetic volcanoes—a case study from Bandas del Sur, Tenerife (Canary Islands), Bull. Volcanol. 75 (7) (2013) 1–19.
[13] F. Kuhl, C.R. Giardina, Elliptic Fourier features of a closed contour, Comput. Graph. Image Process. 18 (1982) 236–258.
[14] M. NASA/METI/AIST/Japan Space Weather, and U.S./Japan ASTER Science Team/ASTER Global Digital Elevation Model V003, 2019 distributed by NASA EOSDIS Land Processes DAAC, doi:10.5067/ASTER/ASTGTM.003.
[15] A. Nieto-Torres, A.L. Martin Del Pozzo, Spatio-temporal hazard assessment of a monogenetic volcanic field, near México City, J. Volcanol. Geotherm. Res. 371 (2019) 46–58, doi:10.1016/j.jvolgeores.2019.01.006.
[16] S.C. Porter, Distribution, morphology, and size-frequency of cinder Cones on Mauna Kea Volcano, Hawaii, Geol. Soc. Am. Bull. 83 (1972) 3607–3612 https://doi.org/10.1130/0016-7606.1972.83[3607:DMASFD]2.0.CO;2.
[17] M. Schmittbuhl, B. Allenbach, J.M. Le Minor, A. Schaaf, Elliptical descriptors: some simplified morphometric parameters for the quantification of complex outlines, Math. Geol. 35 (7) (2003) 853–871.
[18] M.L.C. Soares, S.J. Mayo, R. Gribel, D. Kirkup, Elliptic Fourier analysis of leaf out- lines in five species of Heteropogon (Araceae) from the Reserva Florestal Adolpho Ducke, Manaus, Amazonas, Brazil, Kew Bull 66 (2011) 1–8.
[19] D. Thomas, Elliptical Fourier Shape Descriptors, MATLAB Central File Exchange, 2020 (https://www.mathworks.com/MATLABCentral/fileexchange/12746-elliptical-fourier-shape-descriptors) Retrieved November 20, 2020.

[20] A. Tort, Elliptical Fourier functions as a morphological descriptor of the genus Stenosarina (Brachiopoda, Terebratulida, New Caledonia), Math. Geol. 35 (2003) 873–885, doi:10.1023/B:MATG.0000007784.18452.73.

[21] A. Tort, A. Finizola, The buried caldera of Misti volcano, Peru, revealed by combining a self-potential survey with elliptic Fourier function analysis of topography, J. Volcanol. Geotherm. Res. 141 (2005) 283–297, doi:10.1016/j.jvolgeores.2004.11.005.

[22] C.A. Wood, Morphometric evolution of cinder cones, J. Volcanol. Geotherm. Res. 7 (1980) 387–413.

[23] C.A. Wood, Morphometric analysis of cinder cone degradation, J. Volcanol. Geotherm. Res. 8 (1980) 137–160.

[24] M.C. Zarazúa-Carbajal, S. De la Cruz-Reyna, Morpho-chronology of monogenetic scoria cones from their level contour curves. Applications to the Chichinautzin monogenetic field, Central Mexico, J. Volcanol. Geotherm. Res. 407C (2020) 107093 https://doi.org/10.1016/j.jvolgeores.2020.107093.

[25] M.C. Zarazúa-Carbajal, S. De la Cruz-Reyna, Digital elevation model resolution: effects on the chronometry-oriented morphological analysis of scoria cones in the Sierra Chichinautzin, central Mexico, Geomorphology 389 (2021) 107842, doi:10.1016/j.geomorph.2021.107842.

[26] Michael Gilichinsky, Dmitry Melnikov, Ivan Melekestsev, Natasha Zaretskaya, Moshe Inbar, Morphometric measurements of cinder cones from digital elevation models of Tolbachik volcanic field, central Kamchatka, Canadian Journal of Remote Sensing 36 (4) (2010) 287–300.