Earth Surf. Dynam. Discuss., 2, 357–387, 2014
www.earth-surf-dynam-discuss.net/2/357/2014/
doi:10.5194/esurfd-2-357-2014
© Author(s) 2014. CC Attribution 3.0 License.

Earth Surface Dynamics
Discussions
Open Access

This discussion paper is/has been under review for the journal Earth Surface Dynamics (ESurfD). Please refer to the corresponding final paper in ESurf if available.

Tracing the boundaries of Cenozoic volcanic edifices from Sardinia (Italy): a geomorphometric contribution

M. T. Melis[1], F. Mundula[1], F. Dessì[1], R. Cioni[2], and A. Funedda[1]

[1]Department of Chemical and Geological Sciences, University of Cagliari, Cagliari, Italy
[2]Department of Earth Sciences, University of Firenze, Florence, Italy

Received: 27 April 2014 – Accepted: 29 April 2014 – Published: 28 May 2014

Correspondence to: M. T. Melis (titimelis@unica.it)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Unequivocal delimitation of landforms is an important issue for different purposes, from science-driven morphometric analysis to legal issues related to land conservation. This study is aimed at giving a new contribution to the morphometric approach for the delineation of the boundaries of volcanic edifices, applied to 13 monogenetic volcanoes (scoria cones) related to the Pliocene–Pleistocene volcanic cycle in Sardinia (Italy). External boundary delimitation of the edifices is discussed based on an integrated methodology using automatic elaboration of digital elevation models together with geomorphological and geological observations. Different elaborations of surface slope and profile curvature have been proposed and discussed; among them, two algorithms based on simple mathematical functions combining slope and profile curvature well fit the requirements of this study. One of theses algorithms is a modification of a function already discussed by Grosse et al. (2011), which better perform for recognizing and tracing the boundary between the volcanic scoria cone and its basement. Although the geological constraints still drive the final decision, the proposed method improves the existing tools for a semi-automatic tracing of the boundaries.

1 Introduction

Unequivocal delimitation of landforms is a general objective that needs to be pursued for different purposes, both scientific, such as the general morphometric analysis of a given set of landforms, and applicative, such as the conservation of the natural heritage. The continuously increasing capability of digital elaboration of the DEM (digital elevation model) data gives now the possibility of adopting tools for the automatic recognition and delimitation of specific landforms, and these tools are important for obtaining objective results that are not heavily dependent on the subjective choices of an operator. This assumes particular importance when the delimitation of a given land-

ESURFD

2, 357–387, 2014

CC BY

form is required for conservation purposes, where the delimited area is to be subject to specific regulations or laws.

The morphological and morphometric characteristics of volcanic landforms and edifices have been the object of studies since the end of the 1970s (e.g. Pike, 1978, 1981; Wood, 1980a, b), and overall reviews of the typical values of elevation, base diameter, crater diameter and average slope, and of their variability, are now available (e.g. Francis, 1985; Ollier, 1988; Cas and Wright, 1987; Thouret, 1999; Walker, 2000; Fink, 2000). These studies have been largely used to define the main morphometric parameters of different types of volcanic edifices, and such parameters have been used to discuss and infer their origin, degradation and also age (e.g. Kereszturi et al., 2013). Conversely, to the best of our knowledge, none of the existing studies on volcanic edifice morphometrics have been used for conservation purposes up to now.

As the term volcanic landform is often used with a general meaning to indicate all the surface forms related to volcanic activity, we prefer in the following to use the more specific term "volcanic edifice" to refer to all those landforms formed by accumulation of products around the volcanic vent, both during a single event or as the cumulated result of multiple eruptions. Volcanic edifices largely vary in type and scale: they can be constructional such as monogenetic pyroclastic cones and lava domes at small scale, or composite volcanic massifs and shield volcanoes at large scale, or can be destructional/excavational, such as maars, craters or calderas. Consequently, the external boundary of these edifices can have largely variable sizes and shapes. In this sense, the simplest volcanic edifice is represented by a symmetric, cone-shaped pile of products built upon a planar surface. In this case the edifice boundary is circular-shaped and represented by the concave break in slope at its base (Euillades et al., 2013). Obviously, this represents an extremely simplified, somewhat theoretical case, rarely present in nature.

In their interesting review of volcanic edifice morphometrics, Grosse et al. (2012) discussed how, before the advent of DEMs, the process of delimitation of volcanic edifices, mainly pursued for studies on volcano morphometry, was based on the integrated analysis of topographic maps and air photos with field measurements. Following the large use of DEM, delimitation of volcanic edifices (mainly scoria cones) has been manually performed on the basis of shaded relief images and slope maps (e.g. Fornaciai et al., 2012); the use of dedicated algorithms for semi-automatic and automatic delimitation of volcanic edifices has been recently developed (Grosse et al., 2009, 2012; Euillades et al., 2013). Many authors have used these data for obtaining descriptive morphometric parameters (e.g. base diameter, crater elongation, cone height), or for discussing the relationships between volcanic and tectonic structures (e.g. location of depressions on the crater rim, alignment of cones, azimuths and geometry of the fracture feeding system; Tibaldi, 1995; Mazzarini et al., 2010). The studies of Hooper and Sheridan (1998), Carn (2000), and Kereszturi et al. (2012) analysed the morphometric characteristics of scoria cones in order to estimate possible relationships with their age and to evaluate the extent of erosional processes.

In the framework of the application of the Article 142 of the Italian "Cultural Heritage and Landscape Code", Legislative Decree 42/2004, that states that volcanoes are areas protected by law, a detailed study aimed at identifying and delimiting Cenozoic volcanic edifices present in Sardinia was performed. In order to delimit these areas, a comprehensive morphological, volcanological and morphometrical study was undertaken, proposing a methodology based on the semi-automatic delimitation of the volcanic edifices using a DEM, largely overcoming the subjectivity related to traditional techniques.

In the first phase of this study, a landform classification was used, based on local morphometric attributes such as slope gradient and total curvature (Shary, 1995; Shary et al., 2002; Florinsky, 2012). The results, discussed below, were generally useful to recognize the landforms, but they proved to be unsatisfactory for the identification of their boundaries, as the use of a sole slope classification can hardly represent the morphologic heterogeneity of scoria cone at the regional scale. Therefore, the study was implemented by using the methodology proposed by Grosse et al. (2012), mainly based on two additional geomorphometric parameters (slope and profile curvature),

CC BY

integrated with the use of a new “Grosse-modified” methodology, presented and discussed in detail in the following.

2 Objectives and methods

The main objective of the research was the recognition, selection and delimitation of well-preserved volcanic edifices from the Cenozoic volcanic activity of Sardinia (Italy). The result of this process can then be used by regional authority for adopting conservation measures and to establish development and management policies over the selected landforms. In the present section we present a short geological framework of the Cenozoic volcanism of Sardinia, and the methods adopted in the study. In the following sections, we discuss in detail the morphometric approaches used to get a final delimitation of the selected areas, together with some key examples, which well illustrate the different problems encountered in the research.

Figure 1 is a flow chart showing the general approach used in the study.

2.1 Geological setting and volcanic landforms

During the Cenozoic Sardinia was subject to two distinct volcanic cycles: the Oligocene–Miocene calc-alkaline cycle (32–15 Ma; Lecca et al., 1997) and the Plio-Pleistocene alkaline and tholeiitic cycle (5.1–0.1 Ma; Beccaluva et al., 1985), whose starting phase was recently reconsidered of Messinian age (6.6–6.4 Ma; Lustrino et al., 2007) (Fig. 2, Table 1). The Pliocene–Pleistocene activity, whose products are largely dispersed in Sardinia, was mainly basaltic in composition, varying from mildly to strongly alkaline (mostly with sodic character) to sub-alkaline (with tholeiitic affinity), and shows a marked within-plate geochemical signature (Lustrino et al., 1996, 2000, 2002). Eruptive centres are mainly located, and in some cases aligned, on the main N–S, N60 and N90 structures. A wide range of landforms is associated with the Pliocene–Pleistocene volcanic cycle, mainly represented by extended lava fields, monogenetic

ESURFD
2, 357–387, 2014

CC BY

volcanoes and minor compound volcanoes. Monogenetic volcanoes are mainly represented by scoria cones, distributed in the Logudoro (north-west Sardinia; Beccaluva et al., 1981), in the Orosei-Dorgali areas (central-eastern Sardinia; Lustrino et al., 2002) and in the central Sardinia (Giare). Pliocene–Pleistocene scoria cones span in a time interval from 3.0 ± 0.1 to 0.11 ± 0.02 (Beccaluva et al., 1985). They range from nearly unmodified, poorly eroded cones, characterized by about 30° sloping flanks (Monte Cujaru; Fig. 2), to quite completely eroded remnants where only the conduit zone, occupied by a neck or a dike of coherent magma, is still preserved. Scoria cones were built up on different palaeotopographic surfaces, from planar horizontal or gently dipping (as in the cases respectively of Monte Cujaru and Ibba Manna; Fig. 2), to highly irregular surfaces (Monte Annaru/Poddighe; Fig. 2) which formed on scarps few tens of metres high. Some scoria cones and the related lava fields experienced different degrees of relief inversion occupying highlands extending few or tens of square kilometres, and elevating from tens to hundreds of metres from the surrounding valleys. Finally, all the scoria cones present different products related to a complex constructional activity, such as lava effusions from the flanks or from the base, lateral collapses related to lava effusion, and variable presence of agglutinated scoria banks. These processes reflect on the different amount and distribution of volcanic lithofacies in each scoria cone, determinating the final morphological features.

2.2 Identification of scoria cones

The localization and classification of the volcanic edifices was achieved by integrating data from scientific literature (e.g. Carmignani et al., 2008; Lustrino et al., 2004, and references therein) with an overview of airborne imagery (photo archives of 1968 – b/w, 1977 – colour, respectively at the scale of 1 : 23 000 and 1 : 10 000), orthophotos (http://www.sardegnageoportale.it/navigatori/fotoaeree.html) and web 3-D digital models (Google Earth and Sardegna3D). This analysis allowed the identification of the volcanic landforms such as scoria cones and their relict forms, small shields, craters,

ESURFD
2, 357–387, 2014

CC BY

necks, dikes, lava flows, debris flow deposits, domes and coulees. Selection of the volcanic edifices to be studied and delimited was mainly based on this step.

2.3 DEM pre-processing

A DEM, elaborated in 2011, with 10 m pixel resolution and a vertical and horizontal accuracy of 2.5 m, was used for the study. Based on the general assumption that the smallest object to be generated on the DEM is at least twice the size of the grid (Dikau, 1989), the 10 m resolution was considered satisfactory for the requested final mapping scale of 1 : 25 000 (Melis et al., 2013).

A digital terrain model (DTM) generated by the Cartographic Service of RAS (Autonomous Region of Sardinia) using the 3-D Analyst and Spatial Analyst extensions of ArcGIS 10.0 (ESRI, Redmond, USA) was used. The DTM is georeferenced according to the WGS84 datum (EPSG code: 7030) and UTM projection system (Vacca et al., 2013). The "Contour_Lines" and "Elevation_Points" layers of the 1 : 10 000 scale geographic database (GeoDB 10k) were used as source data. A triangulated irregular network (TIN) was generated and subsequently transformed into a regular grid format. A NoData value was assigned to pixels of the sea surface.

This DEM was pre-processed to verify the quality and to correct the possible artefacts. As indicated by Reuter et al. (2009), the quality of DEM determines the outcomes of geomorphometric analysis. The only DEM noises removed in this research were the artefacts due to wrongly coded elevation contours or due to missing contours. These errors were detected by a hillshade view, and the correction was done by assigning the correct value to the original data. The set of elevation points, available in the original database and used as ground control points during the photogrammetric restitution, was used to improve the quality of the roughness of the land surface with other elevation data rather than the contour lines alone.

ESURFD
2, 357–387, 2014

3 The geomorphometric analysis

Different approaches based on DEM elaborations have been proposed to draw up the boundaries of volcanic edifices after their identification. The methods based on the slope–total curvature relation, as proposed for the general classification of landforms (Vacca et al., 2013) and that proposed by Grosse et al. (2012), are reviewed and, finally, a modification of the Grosse Method (GM) is proposed here, overcoming its inherent complexity, and ultimately reducing the operator choices during the delimitation process.

3.1 Slope / total curvature (S / TC) algorithm

A first approach for a classification aimed at extracting the volcanic edifices as isolated landforms with respect to the surrounding landscape is based on slope and total curvature. The use of these two geomorphometric parameters clearly highlights the presence of a convex upward break in slope, typical of the connection between the edifice and the basement (Euillades et al., 2013). This methodology simplifies those proposed by Iwahashi and Pike (2007) and by Gorini (2009) for landform classification. Slope is a suitable landform parameter in the case of monogenetic edifices, generally characterized by a simple shape often showing a radial symmetry, which clearly stands out with respect to the surrounding basement. The choice of appropriate classes of slope has to be related to the type of edifice, as it is well known that different types of volcanic edifices show different morphological and morphometric features (see for example Pike and Clow, 1981). In the scoria cones analysed in detail for this study, slope classes arising from average morphometric data presented in literature for the same type of landforms were used.

There are several detailed studies on the morphometric characteristics of scoria cones. In order to define the main classes of slope, Fornaciai et al. (2012) presented a statistical analysis for more than 500 scoria cones of various nature and age, ex-

ESURFD
2, 357–387, 2014

CC BY

tracting some basic parameters whose values partly confirm and enlarge the results obtained by Woods (1980a, b):

- The connection between the slope of the cone and the surrounding basement is typically around 3.5°.
- The minimum average gradient of a scoria cone is of about 6°.
- The mean slope value for the large number of studied scoria cones is about 18°, with a standard deviation of ±5°.

Based on the values discussed in these studies, which at a first approximation well agree with the data set of the present research, five classes of slope were used in this step of the study (Table 2).

Slope S (here expressed in degrees) represents the variation of height z in the two directions x and y; it was calculated with the Horn method (Burrough et al.,1998).

$$\text{slope} = \arctan\left(\sqrt{(\mathrm{d}z/\mathrm{d}x)^2(\mathrm{d}z/\mathrm{d}y)^2}\right) \times 57.29578 \quad (1)$$

The curvature K was instead calculated with respect to a 3×3 kernel using the equation of Zevenbergen and Thorne (1987):

$$K = (\partial^2 Z/\partial S^2)/[1+(\partial Z/\partial S)^2]^{3/2}, \quad (2)$$

where S is the maximum slope direction and Z is the quadratic surface calculated as

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I, \quad (3)$$

where the coefficients A to I are the nine elevation values of the nodes of the 3×3 matrix.

The values obtained are positive and negative for convex and concave forms, respectively.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESURFD

2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

Final processing of classification involves the application of the product:

$$M = S \times K. \quad (4)$$

The result is a 10-class subdivision, from −5 (strongly sloping and concave areas) to +5 (strongly sloping and convex areas) with zero (horizontal planar areas) as the central value (Table 2). The output of this process is a map representing, for each pixel, the attribution to 1 of the 10 classes; Fig. 3 shows an extract of the map related to one of the selected scoria cones (Monte Cujaru).

A preliminary delimitation of the volcanic edifice is extracted on the basis of the upper limit of the class representing a concave area with a value of slope less than 6° (class −2). As discussed above, this slope threshold is considered in the literature as the minimum average gradient of a well-preserved cone.

3.2 The Grosse algorithm and the proposed Grosse-modified method

The application of the morphometric classification based on the slope / total curvature algorithm (S / TC) described above presents however some limitations, mainly due to the naturally large variability, in terms of geomorphological and volcanological setting, presented by the studied volcanic edifices. In fact, a unique slope / curvature class is hardly representative of the real basal limit of the scoria cones from Sardinia, mainly due to their different nature, age, basement geology and degree of erosion.

In order to draw up the boundaries of the volcanic edifices with different morphology and age, the approach proposed by Grosse et al. (2012) was applied. In particular the authors, based on the observation that a volcano, although bounded by a major rupture of the slope that connects the flanks of the edifice with the surrounding landscape, generally presents morphological complications that often do not allow an automatic tracing of the perimeter of its base, suggested the use of a morphometric complex function. The method is based on a complex function of two parameters: slope gradient and profile curvature (Wood, 1996).

CC BY

The slope gradient is calculated with the Horn method. The profile curvature (the intersection of the terrain surface with the plane of the z axis and aspect direction) measures the rate of change of the slope along the profile.

The function proposed by Grosse et al. (2012) for the extraction of the boundaries of volcanic edifices (boundary delineation layer) is

$$\text{boundary delineation layer} = \text{profile\_curvature}_{\text{normalized}} x f + \text{slope}_{\text{normalized}}(1 - f), \quad (5)$$

where

$$\text{profile\_curvature}_{\text{normalized}} = (\text{profile\_curvature}_n - \text{profile\_curvature}_{\text{min}}) / \text{profile\_curvature}_{\text{range}} \quad (6)$$

$$\text{slope}_{\text{normalized}} = (\text{slope}_n - \text{slope}_{\text{min}})^2 / (\text{slope}_{\text{range}})^2. \quad (7)$$

f is a weighting factor of the two functions with a suggested value of 0.7 (Grosse et al., 2012) and the subscripts $_n$, $_{\text{min}}$, and $_{\text{range}}$ respectively refer to the point value, the minimum calculated value, and the maximum–minimum calculated range of curvature and slope.

The peculiarity of this function is that it presents a relative minimum corresponding to the boundary between the volcanic edifice and the basement, assuming that this limit has a concave morphology. This method will be referred to here as the "Grosse method" (GM; Grosse et al., 2012).

As clearly stated by the same authors, however, the method does not discriminate locally in the case of a non-concave boundary, which could be the case when the volcanic edifice is built upon a rough, irregular basement, or on top of tectonic lineaments such as faults. The authors suggest applying the function and delineating the edifice boundaries by visual interpretation of the results (i.e. "manually" tracing the path along the minimum values of the generated layer), as the main problem is in general related to the unequivocal distinction of the basement from the edifice.

We propose here a modification of the GM in order to make the edifice much more distinguishable from the surrounding basement in the DEM elaboration. This result was

ESURFD
2, 357–387, 2014

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

obtained by introducing a new function of the same parameters as GM. The proposed algorithm, hereafter referred to as Grosse-modified (GMod), is

$$\text{boundary delineation layer}_{\text{mod}} = \text{profile\_curvature}_{\text{normalized}} x f \times \text{slope}_{\text{normalized}} (1-f). \quad (8)$$

In this case where the value of one of the two parameters is low (as in the case for a nearly planar or a very gentle sloping basement), it decreases the final value of the boundary delineation layer, so strongly differentiating the basement from the rest of the edifice, which is generally characterized by high values in at least one of the two parameters.

The comparison between the resulting images obtained from GM and GMod is shown in Fig. 4. The GMod images are very appropriate to calculate the threshold for masking the area around the volcanic edifice and to delineate the boundary (Fig. 5). Apart from minor local irregularities, largely deviating from the smooth circular shape characterizing scoria cones, and in which manual drawing cannot be avoided, in this way the boundary is generally clearly evidenced around most of the edifice, helping in its automatic tracing.

4 Geological constraints

Parallel to the geomorphometric-based delimitation process, photogeological interpretation, geological map analysis and field survey were performed in order to check and possibly correct the final results. Some general rules can be used in this case.

- Volcanic edifice boundaries cannot cross-cut non-volcanic rocks.
- Pyroclastic edifices such as scoria cones are commonly associated with lava flows erupted from the flank or from the base of the cone.
- Scoria cone can grow on preexisting lava fields. In this case, it is fundamental to distinguish cone-forming deposits from other volcanic products which preceded

ESURFD
2, 357–387, 2014

or post-dated cone formation. In general, we considered as an integral part of the edifice only those deposits that lie on its flanks, so possibly associated with cone-related eruptive vents.

- The deposits related to gravitational processes (e.g. landslides) redistributing the primary cone deposits are here considered part of the edifice.
- In the case of partially eroded edifices in which internal geological features and facies architecture are clearly visible, geology should represent the major constraint for delimiting the inner structure of the edifice from the partially eroded distal products.

The occurrence of various types of deposits can strongly reduce the efficacy of geomorphometric algorithms. For this reason, we suggest that the final delimitation of the cone should always be checked against the observed geological features.

5 Results and discussion

The described methodological approach, based on DEM elaborations, was applied to 13 Plio-Pleistocene scoria cones from Sardinia, with the aim of tracing their boundaries. The results are first discussed with reference to two scoria cones, representative of two endmembers with different degrees of complexity of the landform and of their surroundings. Finally, the general results relative to the 13 delimited scoria cones are also briefly presented. The progressive refinement of edifice boundaries is obtained by the integrated use of the S / TC, the GM, and the GMod algorithms; this methodology clearly shows how the introduction of the GMod algorithm strongly improves the final results.

The simplest case is represented by the Monte Cujaru scoria cone. It is a largely preserved, poorly eroded scoria cone built on a nearly planar surface, characterized by the presence of a summit crater depression, limited by a crater rim elevated about

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESURFD

2, 357–387, 2014

(cc) BY

130 m with respect to the base of the cone, and with an average slope of the flanks of about 30°.

The most complex case is here represented by the Monte Annaru/Poddighe scoria cone. It is an asymmetric cone-shaped relief elevated about 110–180 m above its base, mostly built on a basaltic lava plateau formed by the initial activity of the same eruptive centre. The southern flank of the scoria cone is built upon a tectonic-related plateau elevated about 90–100 m above the surrounding basaltic plain, and constituted by Miocene-age marine sediments (Carmignani et al., 2008). The western flank of the scoria cone experienced a syn-eruptive partial collapse possibly related to lava effusion from the cone base.

5.1 S / TC elaboration

The S / TC elaboration of Monte Cujaru (Fig. 3) shows an approximately concentric, sub-circular distribution of the slope classes. Deviations from circularity arise corresponding to local irregularities, related both to minor, shallow-seated landslides and to the erosional heterogeneities of the surroundings. In the case of Monte Cujaru, the 3.5° slope limit for locating the physical junction between the cone and its basement (as suggested in Fornaciai et al., 2012) is extremely irregular, as it is mainly controlled by erosional features affecting the topographic surface around the scoria cone. Instead, the 6° threshold represents a good first approximation for the edifice boundary, although this limit cannot be considered definitive, due to the extremely irregular trend along the northern limit of the edifice, and due to minor irregularities unrelated from the constructional processes of the edifice.

The S / TC elaboration of Monte Annaru/Poddighe (Fig. 6) shows a discontinuous, approximately concentric, sub-circular distribution of the slope classes. Deviations from circularity affect almost all slope classes in the western sector, in proximity to the collapsed portion of the cone. Other deviations from circularity arise corresponding to the $-2/-3$ and $-3/-4$ classes (Fig. 6a) in the northern and southern flanks, corresponding to morphological irregularities of the surrounding landscape. The $-2/-3$ classes

ESURFD
2, 357–387, 2014

boundary was considered in order to approximate the outer limit of the scoria cone, although this limit, due to its discontinuous trend, cannot be extended to the entire base. The 3.5° threshold in slope (here corresponding to the lower limit of the class −2) does not reflect the smooth circular morphologic nature of scoria cones (Walker, 2000).

This algorithm represents, especially in the case of a nearly regular cone-shaped edifice, a powerful tool to extract a landform from a study area, but – in both the study cases – it does not discriminate satisfactorily the volcano edifice from the basement.

5.2 GM elaboration

On the flanks of the Monte Cujaru cone, the GM elaboration (Fig. 4a) shows a regular concentric pattern of alternating sub-circular red and blue bands (in this representation), representing respectively maximum and minimum of the normalized reference function (Eq. 5). At the base of the scoria cone, in the eastern sector, a wide blue band, representing the relative minimum values, largely overlaps the upper limit of class −2 from the S / TC elaboration, but overall this band cross-cuts different slope classes, smoothing many irregularities which characterize the S / TC based delimitation.

The GM elaboration applied to the more complex case of Monte Annaru/Poddighe shows a similar concentric sub-circular pattern (Fig. 6b). A main blue band well delimitates the base of the cone in the NE sector. Conversely, an important deviation from circularity arises in the southern sector, where the blue bands outline the shape of the surrounding plateau formed by Miocene sediments, and in the NNW sector, where the main blue band marking the base of the edifice in the NE sector shows an irregular, rough trend, and progressively departs from the edifice base toward the east.

As suggested by Grosse et al. (2012), the blue band can be used to "manually" trace the edifice boundary, but some doubts still remain due to discontinuity of this band and to the local occurrence of close multiple minima also in the simplest case. Moreover, several blue-green bands cross-cut the planar topography close to the edifice, highlighting minor topographic irregularities and making the the visual interpretation of the GM elaboration more complex.

ESURFD
2, 357–387, 2014

CC BY

5.3 GMod elaboration

To avoid the problems arising from the S / TC and GM methods and to reduce the dependency from a subjective, operator-driven selection of the edifice boundary, and to improve the accuracy of the results, also the GMod algorithm was applied.

The GMod elaboration of the regular edifice of Monte Cujaru (Fig. 4b) shows a concentric pattern of bands on the flanks of the edifice, and blue scale near concentric irregularly shaped bands in the base zone. The boundary delineation layer in the plain surrounding the edifice has a low and poorly variable value (represented by the black colour in Fig. 4b), with only minor blue zones connecting the edifice to the plain. These transitional, blue-coloured zones are cross cut by black or dark blue narrow bands representing the minimum values. These bands largely overlap with those of the GM elaboration but are reduced in number. At the north-eastern sector, the GM elaboration shows three corresponding blue bands, whereas the pattern shown by the GMod elaboration (from the inner to the outer zone) appears largely simplified. In the same way, in the south-western sector, the two bands evidenced in the GM elaboration reduce to one band and to a steady colour transition.

In the more complex case of Monte Annaru/Poddighe, the GMod elaboration proved to be very useful, as it filters out the evident multiple minima bands of the GM data between the base of the edifice and its surroundings (Fig. 6b and c). In the southern sector, where the morphological features do not reflect the geological characteristics of the base of the cone and of its surroundings, the lithological contact between the Plio-Pleistocene volcanic and Miocene sedimentary rocks drives the delimitation process.

As a general rule, the GMod elaboration reduces the uncertainties related to the occurrence of several repeated bands and presents the advantage of smoothing the morphologic irregularities of the plain surrounding the edifice, simplifying the visual interpretation of the DEM elaborations. It looks self-standing in simple cases (i.e. symmetric cone shape), allowing an automatic tracing for most of the edifice perimeter. In

ESURFD
2, 357–387, 2014

more complex cases where erosion is very impactful, the geological constraints still play a prominent role in the final delimitation of the edifice.

The GMod elaboration has been also applied to 11 other scoria cones, and the resulting boundaries have been extracted to compare and integrate the geological and geomorphological observations. In Fig. 7 the applied GMod classification and the final delimitations of the boundaries are presented. The results are often an intermediate step between the endmember cases discussed above.

6 Conclusions

Scoria cones from Sardinia offer, due to the wide spectrum of age, erosion and forming conditions, resulting in an extremely variable range of shapes, a suitable case study to test the efficiency of existing algorithms and for developing new algorithms aimed at the delimitation of volcanic edifices.

The obtained results, in the case of scoria cone edifices, can be summarized in the following points:

- The S / TC morphometric classification well highlights the shapes of the edifices but does not precisely identify the boundary with the surrounding basement.
- The algorithm introduced by Grosse et al. (2012) performs very well in finding minima in the complex slope / curvature function, but it carries an intrinsic uncertainty for tracing the outer boundary of a volcanic edifice mainly due to its high sensitivity to morphological changes.
- The proposed modification of the method by Grosse (2012), based on a different function of the normalized slope and curvatures for each specific edifice, is helpful in overcoming the problem of manual final tracing of the edifice boundaries, especially in regularly shaped cones.

ESURFD
2, 357–387, 2014

- In more complex shapes derived from eroded cones, geological data still play a key role in tracing the boundary of the volcanic edifices.
- As a consequence, although the presented algorithm reduces the subjectivity of tracing volcanic edifice boundary, and in agreement with what has already been stated by Evans (2012), the complete automatic delimitation of landforms still remains a research frontier.

Acknowledgements. The authors thank the Autonomous Region of Sardinia for the support in this study.

References

Beccaluva, L., Deriu, M., Macciotta, G., Savelli, C., and Venturelli, G.: Carta Geopetrografica del Vulcanismo Plio-Pleistocenico della Sardegna Nord Occidentale, Scala 1 : 50 000, Grafiche STEP cooperativa, Parma, 1981.

Beccaluva, L., Civetta, L., Macciotta, G., and Ricci C. A.: Geochronology in Sardinia: results and problems, Rendiconti della Società Italiana di Mineralogia e Petrologia, 40, 57–72, 1985.

Beccaluva, L., Brotzu, P., Macciotta, G., Morbidelli, L., Serri, G., and Traversa, G.: Cenozoic tectono-magmatic evolution and inferred mantle sources in the Sardo-Tyrrhenian area, in: The Lithosphere in Italy: Advances in Earth Science Research, Accademia Nazionale dei Lincei, Roma, 229–248, 1987.

Burrough, P. A. and McDonell, R. A.: Principles of Geographical Information Systems, Oxford University Press, New York, 1998.

Carmignani, L., Oggiano, G., Funedda, A., Conti, P., Pasci, S., and Barca, S.: Carta Geologica della Sardegna a scala 1 : 250 000, Litografia Artistica Cartografica s.r.l., Firenze, 2008.

Carn, S.: The Lamongan volcanic field, East Java, Indonesia: physical volcanology, historic activity and hazards, J. Volcanol. Geoth. Res., 95, 81–108, 2000.

Cas, R. A. F. and Wright, J. V.: Volcanic Successions, Modern and Ancient, Allen and Unwin, London, 1987.

Dikau, R.: The application of a digital relief model to landform analysis, in: Three Dimensional Application in Geographical Information Systems, edited by: Irt Raper, J. F., Taylor & Francis, London, 55–77, 1989.

Euillades, L., Grosse, P., and Euillades, P.: NETVOLC: an algorithm for automatic delimitation of volcano edifice boundaries using DEMs, Comput. Geosci., 56, 151–160, 2013.
Evans I. S.: Geomorphometry and landform mapping: what is a landform?, Geomorphology, 137, 94–106, 2012.
Favalli, M., Karátson D., Mazzarini, F., Pareschi M. T., and Boschi, E.: Morphometry of scoria cones located on a volcano flank: a case study from Mt. Etna (Italy), based on high-resolution LiDAR data, J. Volcanol. Geoth. Res., 186, 320–330, 2009.
Fink, J. H. and Anderson, S. W.: Lava domes and coulees, in: Encyclopedia of Volcanoes, edited by: Sigurdsson, H., Houghton B. F., McNutt S. R., Rymer, H., and Stix, J., Academic Press, San Diego, 643–662, 2000.
Florinsky, I. V.: Digital terrain modeling: a brief historical overview, in: Digital Terrain Analysis in Soil Science and Geology, Elsevier, Amsterdam, 1–4, 2012.
Fornaciai, A., Favalli, M., Karátson, D., Tarquini, S., and Boschi, E.: Morphometry of scoria cones, and their relation to geodynamic setting: a DEM-based analysis, J. Volcanol. Geoth. Res., 217–218, 56–72, 2012.
Francis, P.: Volcanoes: a Planetary Perspective, Oxford University Press, Oxford, 1993.
Gorini, M. A. V.: Physiographic classification of the ocean floor: a multi-scale geomorphometric approach, in: Proceeding of Geomorphometry Conference, edited by: Purves, R., Gruber, S., Straumann, R., and Hengl, T., 98–105, 2009.
Grosse, P., van Wyk de Vries, B., Petrinovic, I. A., Euillades, P. A., and Alvarado, G.: Morphometry and evolution of arc volcanoes, Geology, 37, 651–654, 2009.
Grosse, P., van Wyk de Vries, B., Euillades, P. A., Kervyn, M., and Petrinovic, I. A.: Systematic morphometric characterization of volcanic edifices using digital elevation models, Geomorphology, 136, 114–131, 2012.
Hasenaka, T.: Size, distribution, and magma output rate for shield volcanoes of the Michoacán-Guanajuato volcanic field, Central Mexico. J. Volcanol. Geoth. Res., 63, 13–31, 1994.
Hasenaka, T. and Carmichael, I.: A compilation of location, size and geomorphological parameters of the volcanoes of the Michoacán-Guanajuato volcanic field, México, Geofısica Internacional, 24, 577–607, 1985.
Hooper, D. and Sheridan, M.: Computer-simulation models of scoria cone degradation, J. Volcanol. Geoth. Res., 83, 241–267, 1998.

CC BY

Iwahashi, J. and Pike, R. J.: Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature, Geomorphology, 86, 409–440, 2007.
Kereszturi, G., Jordan, G., Németh, K., and Doniz-Paez, J. F. Syn-eruptive morphometric variability of monogenetic scoria cones, B. Volcanol., 74, 2171–2185, doi:10.1007/s00445-012-0658-1, 2012.
Kereszturi, G., Geyer, A., Martí, J., Németh, K., and Dóniz-Páez, F. J.: Evaluation of morphometry-based dating of monogenetic volcanoes – a case study from Bandas del Sur, Tenerife (Canary Islands), B. Volcanol., 75, 734–753, 2013.
Lecca, L., Lonis, R., Luxoro, S., Melis, E., Secchi, F., and Brotzu, P.: Oligo-Miocene volcanic sequences and rifting stages in Sardinia: a review, Period. Mineral., 66, 7–61, 1997.
Lustrino, M., Melluso, L., Morra, V., and Secchi, F.: Petrology of Plio-Quaternary volcanic rocks from central Sardinia, Period. Mineral., 65, 275–287, 1996.
Lustrino, M., Melluso, L., and Morra, V.: The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy), Earth Planet. Sc. Lett., 180, 259–270, 2000.
Lustrino, M., Melluso, L., and Morra, V.: The transition from alkaline to tholeiitic magmas: a case study from the Orosei-Dorgali Pliocene volcanic district (NE Sardinia, Italy), Lithos, 63, 83–113, 2002.
Lustrino, M., Morra, V., Melluso, L., Brotzu, P., D'Amelio, F., Fedele, L., Lonis, R., Franciosi, L., and Petteruti Liebercknect, A. M.: The Cenozoic igneous activity in Sardinia, Period. Mineral., 73, 105–134, 2004.
Lustrino, M., Melluso, L., and Morra, V.: The geochemical peculiarity of "Plio-Quaternary" volcanic rocks of Sardinia in the circum-Mediterranean Cenozoic Igneous Province, in: Cenozoic Volcanism in the Mediterranean Area, edited by: Beccaluva, L., Bianchini, G., and Wilson, M., Geological Society of America Special Paper, 418, 277–301, 2007.
Mazzarini, F., Ferrari, L., and Isola, I.: Self-similar clustering of cinder cones and crust thickness in the Michoacan–Guanajuato and Sierra de Chichinautzin volcanic fields, Trans-Mexican Volcanic Belt, Tectonophysics, 486, 55–64, 2010.
Melis, M. T., Loddo, S., Vacca, A., and Marrone, V. A.: Applicazione di un metodo di analisi geomorfometrica a supporto della cartografia pedologica in Sardegna, 17a Conferenza Nazionale ASITA, Riva del Garda, Italy, 5–7, 993–1000, 2013.

ESURFD
2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

CC BY

Mundula, F., Cioni, R., and Mulas, M.: Rheomorphic diapirs in densely welded ignimbrites: the Serra di Paringianu ignimbrite of Sardinia, Italy, J. Volcanol. Geoth. Res., 258, 12–23, 2013.
Mundula, F., Cioni, R., and Rizzo, R.: A simplified scheme for the description of textural features in welded ignimbrites: the example of San Pietro Island (Sardinia, Italy), Ital. J. Geosci., 128, 615–627, 2009.
Ollier, C.: Volcanoes, Blackwell, Oxford, 1988.
Pike, R. J.: Volcanoes on the inner planets-Some preliminary comparisons of gross topography, in: Lunar and Planetary Science Conference, 9th, Houston, Tex Proceedings, 3, A79-39253 16-91, Pergamon Press, Inc., New York, 3239–3273, 1978.
Pike, R. J. and Clow G. D.: Revised Classification of Terrestrial Volcanoes and a Catalog of Topographic Dimensions with New Results on Edifice Volume, US Geological Survey Open-File Report OF 81-1038, 1981.
Reuter, H. I., Hengl, T., Gessler, P., and Soille, P.: Preparation of DEMs for geomorphometric analysis, in: T. Geomorphometry: Concepts, Software, Applications, edited by: Hengl, T. and Reuter, H. I., Elsevier, Amsterdam, 227–254, 2009.
Rossi, M. J.: Morphology and mechanism of eruption of postglacial shield volcanoes in Iceland, B. Volcanol., 57, 530–540, 1996.
Shary, P. A.: Land surface in gravity points classification by a complete system of curvatures, Math. Geol., 27, 373–390, 1995.
Shary, P. A., Sharaya, L. S., and Mitusov, A. V.: Fundamental quantitative methods of land surface analysis, Geoderma, 107, 1–32, 2002.
Thouret, J. C.: Volcanic geomorphology – an overview, Earth Sci. Rev., 47, 95–131, 1999.
Tibaldi, A.: Morphology of pyroclastic cones and tectonics, J. Geophys. Res., 100, 24521–24535, 1995.
Vacca, A., Loddo, S., Melis, M. T., Funedda, A., Puddu, R., Verona, M., Fanni, S., Fantola, F., Madrau, S., Marrone, V. A., Serra, G., Tore, C., Manca, D., Pasci, S., Puddu, M. R., and Schirru, P.: A. GIS based method for soil mapping in Sardinia, Italy: a geomatic approach, J. Environ. Manage., 138, 87–96, 2014.
Walker, G. P. L.: Basaltic volcanoes and volcanic systems, in: Encyclopedia of Volcanoes, edited by: Sigurdsson, H., Houghton, B. F., McNutt, S. R., Rymer, H., and Stix, J., Academic Press, San Diego, 283–290, 2000.
Wood, C. A.: Morphometric evolution of cinder cones, J. Volcanol. Geoth. Res., 7, 387–413, 1980a.

ESURFD
2, 357–387, 2014

CC BY

Wood, C. A.: Morphometric analysis of cinder cone degradation, J. Volcanol. Geoth. Res., 8, 137–160, 1980b.
Wood, J.: The Geomorphological Characterization of Digital Elevation Models, Ph.D. thesis, University of Leicester, Department of Geography, Leicester, UK, 1996.
Zevenbergen, L. W. and Thorne, C. R.: Quantitative analysis of the land surface topography, Earth Surf. Proc. Land., 12, 47–56, 1987.

ESURFD
2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

CC BY

Table 1. List of the scoria cones analyzed, surface of the base end and radiometric age.

Code	Name	Location	Lat centroid	Long centroid	Area (km^2)	K/Ar age (Ma)
1	Monte Massa	PLOAGHE	1 478 090	4 507 120	0.34	0.38 ± 0.04
2	Monte Aurtidu	TORRALBA	1 483 410	4 484 150	0.27	0.4 ± 0.1
3	Monte'Oes	TORRALBA	1 480 750	4 484 890	0.29	0.4 ± 0.2
4	Monte Pelau	THIESI	1 477 390	4 487 950	1.22	1.9 ± 0.1
5	Zeppara Manna	GENONI	1 493 740	4 403 420	0.58	2.76 ± 0.11
6	Ibba Manna	BARI SARDO	1 555 870	4 411 920	0.17	
7	Punta Su Nurtale	ONIFAI	1 557 160	4 472 680	0.16	
8	Monte Pubulena	PLOAGHE	1 477 530	4 497 580	0.11	0.9 ± 0.4
9	Monte Ruju	SILIGO	1 477 910	4 495 680	0.10	0.6 ± 0.1
10	Monte Percia	SILIGO	1 478 320	4 496 080	0.04	0.6 ± 0.1
11	Monte Cuccuruddu	CHEREMULE	1 476 520	4 483 540	0.12	0.11 ± 0.02
12	Monte Cujaru	BONORVA	1 486 150	4 480 380	0.51	0.8 ± 0.1
13	Monte Annaru/Poddighe	GIAVE	1 479 240	4 479 730	0.69	> 0.2

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
ESURFD
2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

CC BY

Table 2. Slope classification.

Slope classes	Value expressed in degrees
1	< 3.5
2	3.5–6
3	6–13
4	13–18
5	> 18

ESURFD
2, 357–387, 2014

CC BY

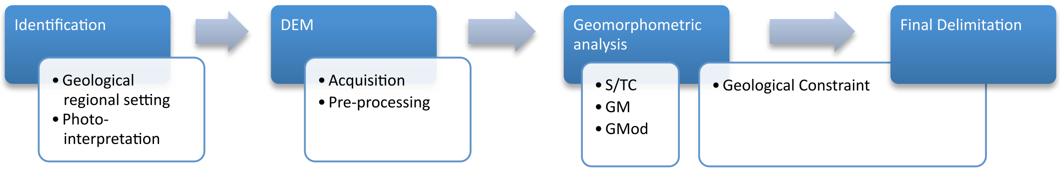


Figure 1. Schematic flow chart of the proposed methodology for the delimitation of the boundaries of the volcanic edifices with the three morphometric classifications discussed in the text.

ESURFD
2, 357–387, 2014

CC BY

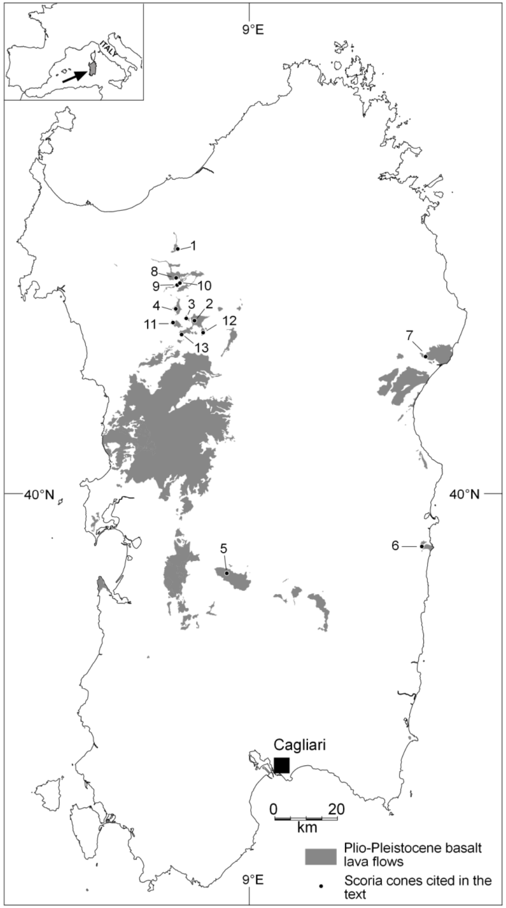


Figure 2. Distribution of Plio-Pleistocene basalt lava flows in Sardinia and localization of the scoria cones (the codes refer to the list in Table 2).

ESURFD
2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

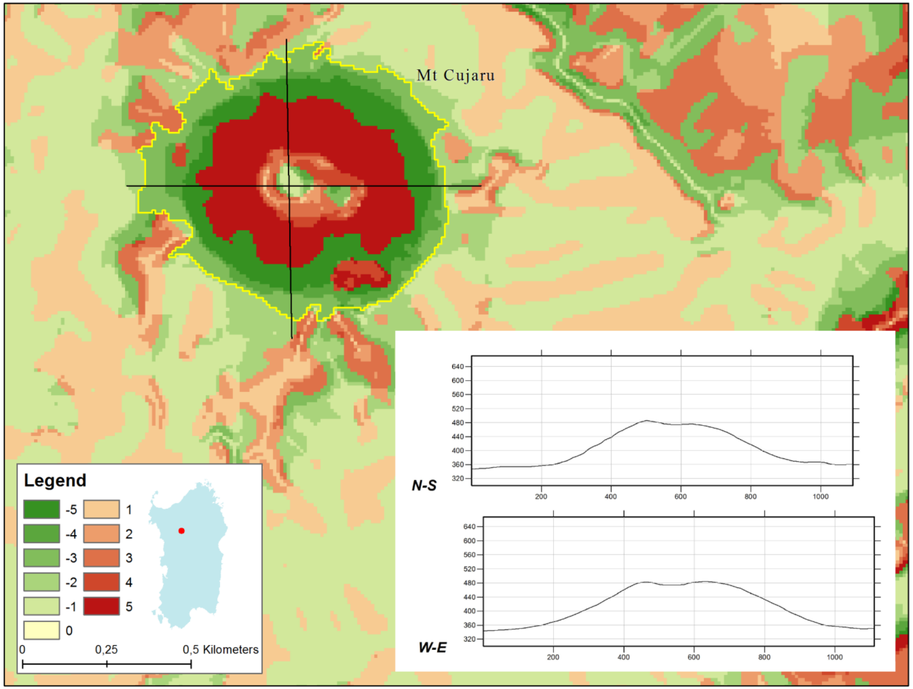


Figure 3. S/TC morphometric classification and topographic profiles of Monte Cujaru. In yellow is the boundary of the volcanic edifice extracted from the transformation in polyline of the limit of the class −3.

ESURFD

2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

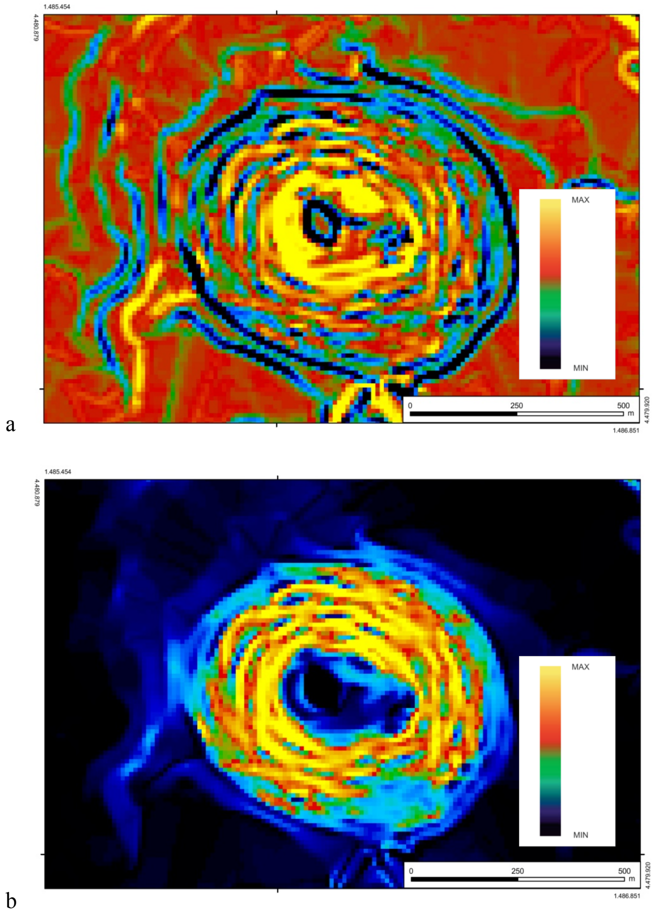
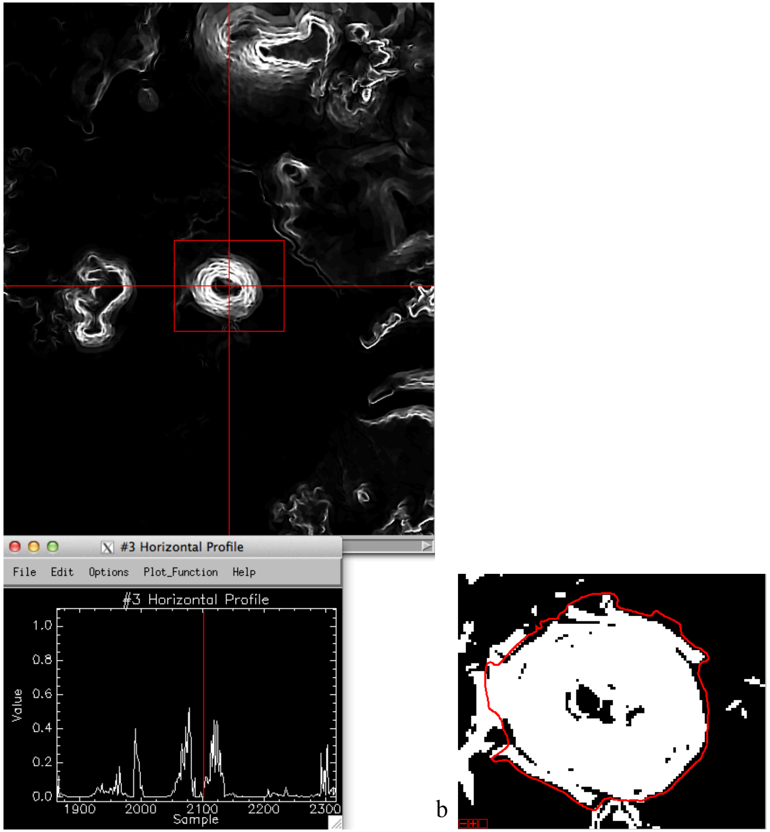


Figure 4. Comparison between the resulting image obtained with the application of **(a)** Grosse's method (GM) and **(b)** modified Grosse's method (GMod) to the area of Mt Cujaru.

ESURFD
2, 357–387, 2014

CC BY



a b

Figure 5. Application of the Grosse's modified method to the DEM of Mt Cujaru: **(a)** the horizontal profile enhances the minimum and maximum values (thresholds) to apply a mask to the image and to classify the data; **(b)** mask image (0 in black and +1 in white). In red is the final boundary.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESURFD
2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

CC BY

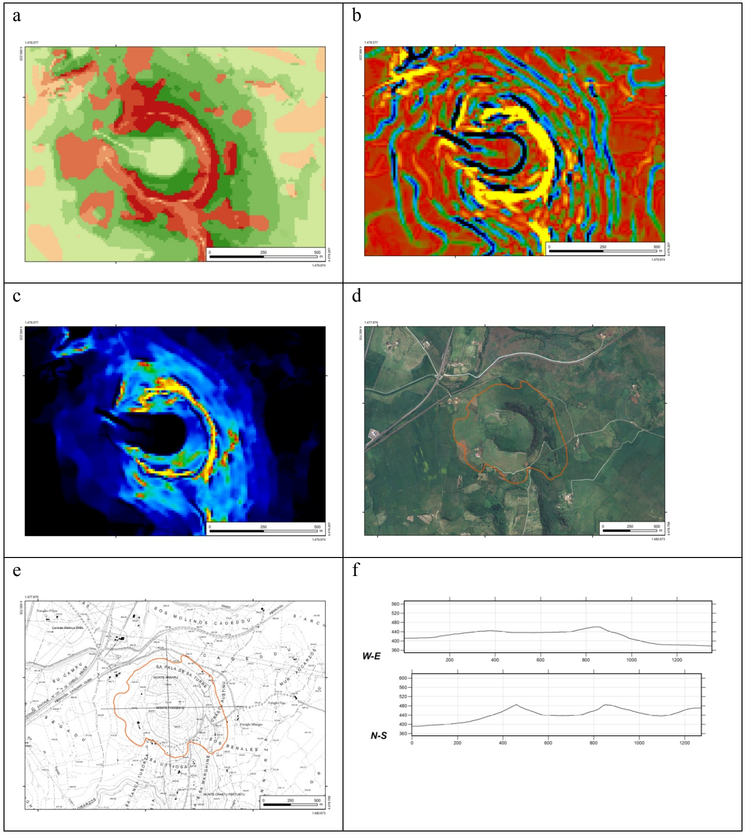


Figure 6. Mt Annaru/Poddighe: **(a)** first morphometric classification (legend in Fig. 1); **(b)** Grosse's method; **(c)** modified Grosse's method; **(d)** aerial photograph and in red the final boundary; **(e)** topographic map with the final boundary; **(f)** topographic profiles of the volcanic edifice, with the traces designed in the map on the left. The legend for the classifications of **(b)** and **(c)** is in Fig. 3.

ESURFD
2, 357–387, 2014

Tracing the boundaries of Cenozoic volcanic edifices

M. T. Melis et al.

CC BY

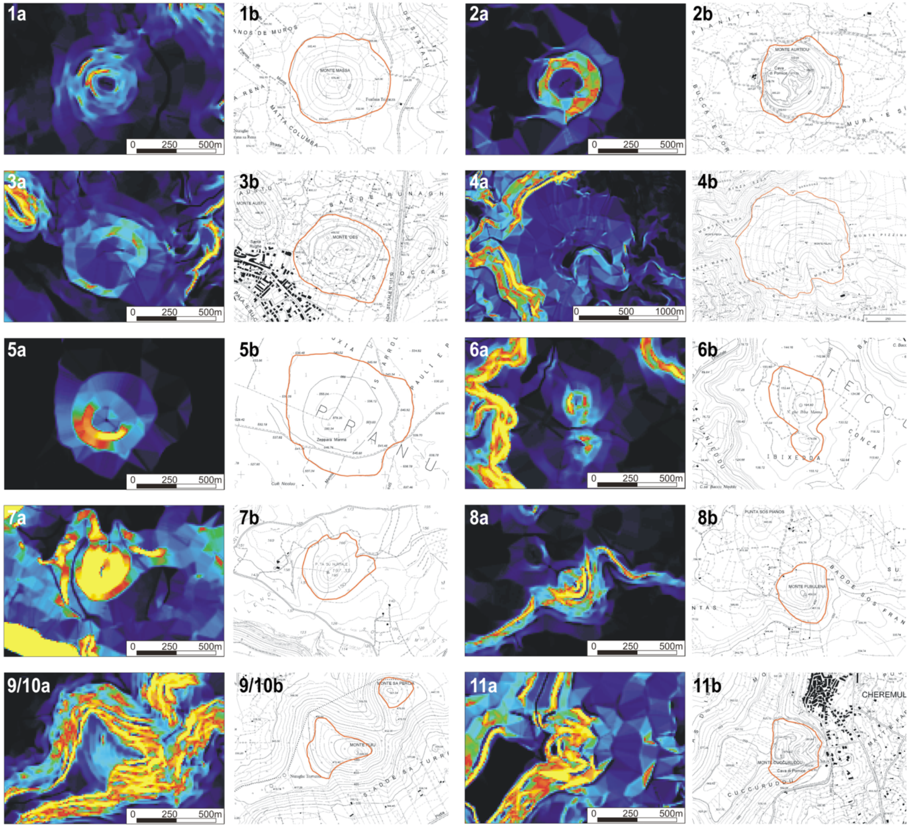


Figure 7. In this figure the applied GMod classification and the final delimitations of the boundaries are overlaid on the topographic map. The numbers of the edifices refer to Table 1.