ORIGINAL PAPER

A case study comparing landscape metrics to geologic and seismic data from the Ischia Island (Southern Italy)

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Abstract In this paper, a high-resolution digital elevation model (DEM) of the Ischia Island has been created, and a digital terrain analysis has been carried out to identify of morphostructural elements of this landscape. Ischia is an active volcano located in the Western sector of the Gulf of Naples that is characterized by historical and recent volcano-tectonic activity. The local kinematics is unclear, and so identification of tectonic lineaments might elucidate recent tectonic processes. We identify morphostructural features using geomorphic parameters derived from analysis of the high-resolution DEM. Successively, the comparison with known geologic features provides validation of the extracted morphotectonic data. We found that one of the main directions of the morphostructural lineaments extracted is consistent with the regional NE–SW extensional stress field; moreover, the lineaments on the northern flank of Mt. Epomeo are strictly correlated with the mapped faults that have a history of strong and moderate earthquakes. The technique implemented for this study area allowed us to identify new original morphostructural lineaments in a reproducible way that may be useful for investigating various landscapes where field survey is not possible. Indeed, the extracted lineaments represent potential active faults near the northern coast of the Ischia Island, where both seismicity and intense urbanization delineate a high seismic risk.

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Introduction

Digital elevation models (DEMs) provide a representation of Earth's topography (Dymond et al. 1995; Miliaresis and Argialas 2002) from which various quantitative metrics may be extracted to allow automatic interpretation of terrain features and to characterize various processes affecting the landscape (Jordan 2003). Moreover, quantitative analysis of the topographic features contributes to study the interaction between tectonics and surface processes, providing a basis for modelling landscape evolution. Particularly, geo-morphometrical analysis of DEMs represents a methodology for studying the morphotectonics of an area quantitatively recognizing the tectonic structures (e.g., Jordan et al. 2005).
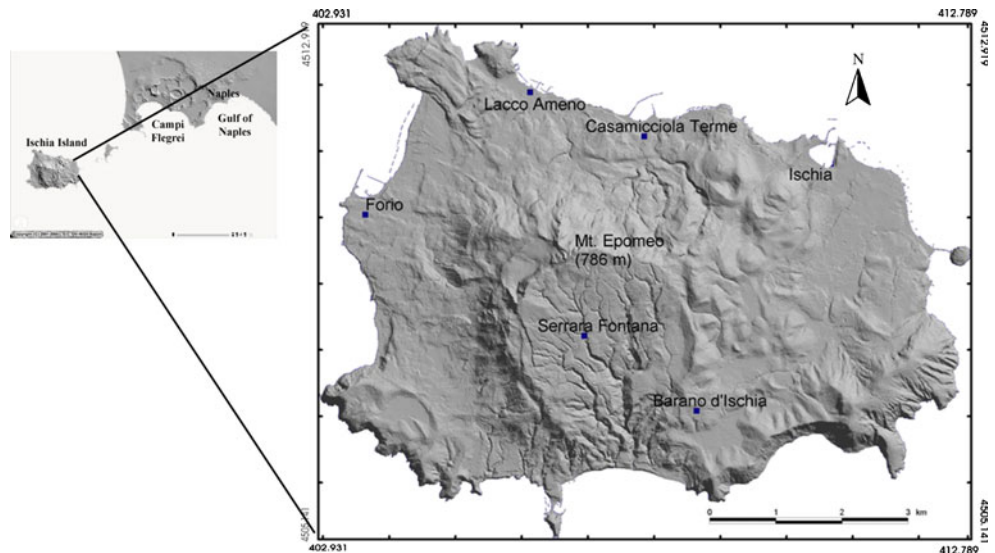
The Ischia Island has been extensively studied through conventional geological approach (Vezzoli 1988; Tibaldi and Vezzoli 2004), but digital terrain analysis has never been performed. In particular, the general lack of modern detailed structural geomorphological mapping has not permitted an exhaustive analysis of the morphostructural characteristics of the island. Therefore, a high-resolution DEM (2×2 m pixel) of the island has been produced in our work in order to identify original new structural lineaments through image analysis techniques (Hilley and Arrowsmith 2000; Jordan 2003; Mitasova and Hofierka 1993). A density map of historical and instrumental earthquakes overlain on the ortophoto (pixel 1 m) from Compagnia Generale Ripreseaeree, airborne 2000 of the Ischia Island has been produced in order to give a preliminary contribution to the seismic risk assessment.

Study area

The Ischia Island (Southern Italy) is located inside of the
Campanian volcanic province at the northwestern side of
the Gulf of Naples, which also includes the Campi Flegrei
volcanic field (Fig. 1). The most important events that have
characterized the volcano-tectonic historical and recent
activity of the island have been caldera resurgence, slope
instability, and seismicity. The island is dominated by the
Mt. Epomeo (787 m), which is located in its central–
western sector. It has been interpreted as a volcano-tectonic
horst (Fusi et al. 1990; Gillot 1985; Rittman 1930; Vezzoli
1988) caused by the resurgent caldera (Orsi et al. 1991).
Volcanic activity begun around 150 kiloyears (ky) ago
(Cassignol and Gillot 1982) and continued, with quiescence
periods, until 1302 A.D., when the Arso lava flow eruption
took place. In the last 30 ky, an uplift of about 900 m has
occurred (Orsi et al. 1991). The uplift has been controlled

by a set of sub-parallel NW–SE to N–S striking faults in the
western sector of Mt. Epomeo and by NE–SW to E–W
faults in its northern sector (Fig. 2). In the eastern sector of
the island, N–S and NE–SW striking fractures and faults
control the location of the vents (Fig. 8a, Foglio CARG
2010).

Slope instability is mainly concentrated in the northern
and western sectors of the Island and in the southern flank
of Mt. Epomeo (Del Prete and Mele 1999; Guadagno and
Mele 1995; Mele and Del Prete 1998; Tibaldi and Vezzoli
2004). The instability along steep slopes has been generated
by the resurgence of the caldera as the result of gravita-
tional instability and faulting.

The strongest historic earthquakes (VIII<I<X MCS)
occurred in the eighteenth and nineteenth centuries (Cubellis
and Luongo 1998; CPTI 2004; Luongo et al. 2006), and
the destructive events of 1881 (I=VIII MCS) and 1883
(I=X MCS) occurred in the northern sector of the Island
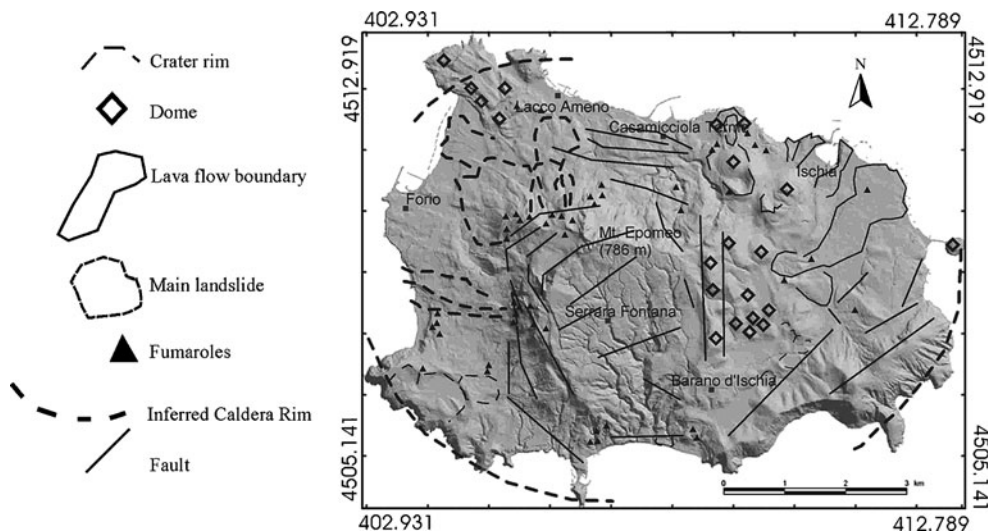
and induced landslides in this zone (Violante et al. 2003). According to Chiocci and De Alteriis (2006), the southern flank of Mt. Epomeo represents the remnant of a giant landslide that produced a huge debris avalanche in prehistorical times; currently, this sector is affected by deep incisions and numerous debris flows (Tibaldi and Vezzoli 2004).

The Ischia Island has been characterized by intense hydrothermal activity, which includes fumaroles, hot springs, and diffuse degassing areas (Chiodini et al. 2004). This activity is concentrated along faults bounding the northern and western flanks of Mt. Epomeo (Fig. 2). Leveling surveys and space-borne Synthetic Aperture Radar images collected between 1993 and 2003 indicate that the flanks of Mt. Epomeo have shown subsidence with a rate of 1.27 cm/year (Manzo et al. 2006; Sepe et al. 2007).

Generation of high resolution DEM

The generation of a DEM is a fundamental step for a reliable digital topographic analysis. The DEM accuracy has a great influence on the interpretation of results obtained by terrain analysis, and it depends on the data source, the interpolation method, and the gradient calculation algorithm (Moore et al. 1993). We used digitized contour maps and spot elevation in vector format (scale 1:2,000) provided by the Consorzio Intercomunale Servizi Ischia to produce a high-resolution DEM of the area. Contour maps were produced by stereo aerial photographic methods using photos taken on July 22, 1998 (released in August 2000), which consist of 36 sheets in DXF format. A quality control and editing step has been necessary in order to rectify or eliminate incorrect elevation data extracted

from the original data (contour lines and elevation points). These data were processed in the framework of the DPC Project V3_03-Ischia, 2004–2006.

We have used the triangulation irregular network interpolation technique through ArcGIS ESRI Software since it is a fast method for generating DEM, but our experience showed that this analysis had to be augmented using additional data including vector data of the coastal line derived from both the digital color orthophoto (pixel 1 m) from Compagnia Generale Ripreseaeree, airborne 2000 and an IKONOS satellite image (RGB, pixel 1 m) acquired on the August 9, 2000. The final dataset, consisting of about 6.5 million elevation points, has been used for generating the digital elevation model through the kriging interpolation linear method which is appropriate for carrying out morphometric analysis on this DEM. This process produced a 2×2-m DEM with an elevation range spanning 0 to 787.4 m (Nappi et al. 2006). The DEM (Fig. 3) is referenced to UTM zone 33 with the WGS-84 ellipsoid.

Description of geomorphic quantitative analysis

Geologic events deform Earth's surface to various degrees and alter the physical and chemical nature of rocks near the surface. This deformation and alteration may be expressed in the form of topography. Particularly, geologic structures may produce linearly aligned features not typically encountered in nature, and so, recognizing, measuring, and interpreting all the linear and aerial surface features is of great importance in geodynamics.

Although the interpretation of land morphology applied to tectonic deformation has been broadly studied, there are few examples of integration of digital methods for tectonic
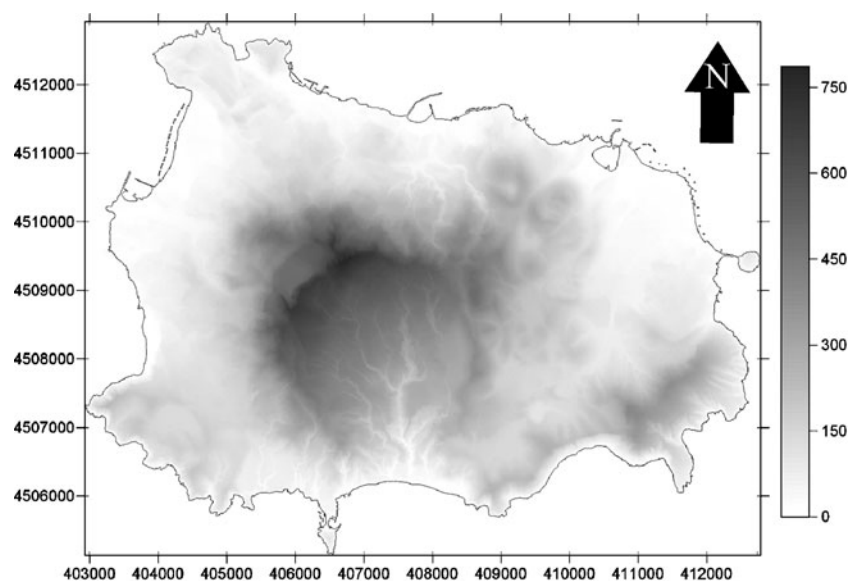

Fig. 3 Digital Elevation Model of the Ischia Island (pixel 2×2m) processed for the DPC Project V3_03-Ischia, 2004–2006

geomorphology with the classical approach (Burbank and Anderson 2001, Keller and Pinter 2002, Jordan et al. 2005; Nappi et al. 2009).

Structural discontinuities in rocks most often result in linear morphological features along the intersection of fractures/fault planes and the land surface. Intersection of bedding and the topographic surface can appear as linear features or planar features in DEMs. Curved or even circular patterns are most commonly associated with plutons, volcanic cones, and calderas. Linear morphological expressions of fractures include: linear valleys, linear ridgelines, and linear slope breaks.

To identify these features using digital data, a lineament is a continuous series of pixels having a similar value of terrain metric. Linear fracture traces are most visible in the case of normal, reverse and strike-slip faults with steep planes, while thrust faults have an irregular topographic expression (Drury 1987; Prost 1994; Goldsworthy and Jackson 2000). Intersection of the topographic surface and fold structures can also result in linear and planar features depending on the geometry and orientation of the folds with respect to the erosion surface (e.g., Mynatt et al. 2007). Uniform hillsides (planar features) develop along folds. Geometrical parameters of planar surfaces are described by uniform terrain aspect and constant slope values.

Large elongated areas of uniform terrain aspect and terrain slope with linear boundaries may be associated with faults. The measure of curvature is important in cases of complex fracture surfaces. The asymmetry of slope values across valleys and ridgeline axes, revealed by slope angle differences, can be caused by tectonics.

High values of topographic residual surface might correlate with rapidly uplifting areas and could reveal the footwall of an active normal fault (Hilley and Arrowsmith 2000).

The main geometric characteristics of a single linear feature are the continuity of orientation and length, and the curvature, in case of curved lines (Jordan and Csillag 2003). The spatial distribution and statistical relationships among lineaments are calculated by length and orientation frequencies for the entire study area.

It is necessary to highlight that morphological features, such as linear valley lines, asymmetric slopes, and depressions, may be caused by secondary processes or can be associated to differential erosion due to lithology. In this sense, morphometric analysis must be interpreted with caution, since offsets occurred long ago could be expressed as coherent linear features due to differential erosion.

Extraction of morphometric parameters from the DEM

Image processing techniques are among the most used methods for locating and mapping structural lineaments (Carrere 1990; Gonzales and Wintz 1987; Math et al. 1995). The criteria of lineament extraction is based on the identification of linear topographic surface features, such as valleys, ridges, breaks in slope, boundaries of elevated areas aligned in a rectilinear or slightly curvilinear shape, and that distinctly differ from the patterns of adjacent features (Jordan et al. 2005). Elevation and derivatives of altitude are the base for geomorphometric study of landscape (Evans 1972, 1980; Mitasova and Hofierka 1993).

The morphometric parameters concerned in our work and described in the next sections (*terrain slope*, *terrain aspect*, *tangential curvature*, *profile curvature*, *shaded relief*, *topographic residual surface*) have been extracted following the methods of Moore et al. (1993).

The terrain slope $S = [(dH/dx)(2) + (dH/dy)(2)](1/2)$ measures the slope at any grid node on the surface. For a particular point on the surface, the terrain slope is based on the direction of the steepest descent or ascent at that point, may change across the surface. We have analyzed and mapped the linear continuity of this parameter to highlight the presence of scarps and slope breaks that could be associated with fault lines at surface in the Ischia Island. Moreover, we carried out a statistical analysis of the azimuthal distribution of the morphostructural lineaments extracted through this methodology. The thematic map of Fig. 4 shows the rose diagram of the lineaments.

The terrain aspect $A_t = \arctan[(-dH/dy)/(dH/dx)]$ measures the downhill direction of the steepest slope (i.e., dip direction) at each grid node. The continuous crest lines shown by this morphometric parameter have been extracted from the DEM of the Ischia Island to identify linear geomorphic features that may possibly be associated with footwalls of normal faults.

The tangential Curvature K_T measures the topographic surface curvature in the direction perpendicular to the maximum gradient direction or tangential to the contour lines:

$$K_T = \frac{\left(\frac{\partial^2 z}{\partial x^2}\right)\left(\frac{\partial z}{\partial y}\right)^2 - 2\left(\frac{\partial^2 z}{\partial x \partial y}\right)\left(\frac{\partial z}{\partial x}\right)\left(\frac{\partial z}{\partial y}\right) + \left(\frac{\partial^2 z}{\partial y^2}\right)\left(\frac{\partial z}{\partial x}\right)^2}{pq^{1/2}} \quad (1)$$
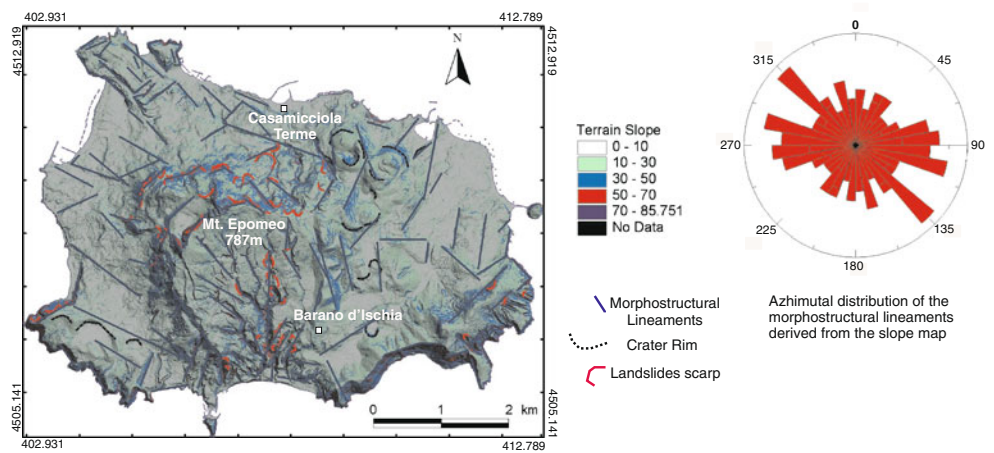
$$p = \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2$$

$$q = 1 + p$$

The profile curvature K_p quantifies the rate of change in slope along the direction of maximum slope:

$$K_p = \frac{\left(\frac{\partial^2 z}{\partial x^2}\right)\left(\frac{\partial z}{\partial x}\right)^2 + 2\left(\frac{\partial^2 z}{\partial x \partial y}\right)\left(\frac{\partial z}{\partial x}\right)\left(\frac{\partial z}{\partial y}\right) + \left(\frac{\partial^2 z}{\partial y^2}\right)\left(\frac{\partial z}{\partial y}\right)^2}{pq^{3/2}} \quad (2)$$

Fig. 4 The terrain slope map shows the morphostructural features extracted: the lineaments (*blue lines*), the landslides scarps (*in red*), and the crater rims (*in dashed black*). The *rose diagram* represents the frequency distribution of the lineament directions

$$p = \left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2$$

$$q = 1 + p$$

Negative values of both tangential curvature and profile curvature indicate that the surface is upwardly convex; positive values show that the surface is upwardly concave. A curvature value of zero indicates that the surface is flat.

We low-pass filtered and classified the DEM and identified the highest values of tangential and profile curvature to outline basins/ridges. Moreover, the continuous topographic features related to those parameters have been plotted and analyzed using rose diagrams over the whole study area (Fig. 5).

Additionally, we used shaded relief models of the topography (elevation angles 10°, 30°, and 45°; azimuthal coverage: for each elevation angle, one image spaced out 30° from one another, clockwise starting from North) (Carrere V 1990) to visually identify linear features based on contrast between light and dark tones in the image. Such

lineaments have been enhanced by overlaying them on the Ischia orthophoto (airborne Italy 2000) and on the elevation contour map to verify their consistency with valleys, ridges, and slope breaks (Fig. 6). The azimuthal distribution of the extracted lineaments have also been performed.

The topographic residual surface represents a measure of relief within the landscape. This parameter indicates how suddenly channels are incised into the landforms (Hilley and Arrowsmith 2008). In areas undergoing rapid uplift, as an active tectonic area, channels will incise steeply into the surrounding soil. Therefore, high values of residual surface should correlate with rapidly uplifting areas.

The residual surface is calculated by subtracting two derived surfaces: the envelope and the sub-envelope surfaces. The envelope is a surface interpolated from the stream bottoms in a landscape, and the sub-envelope is a surface interpolated from the ridge lines in a landscape. The final distribution of the topographic residual value depends on the points selected for the envelope and sub-envelope surfaces.

The topographic residual surface for the Ischia Island has been calculated using the algorithm of Hilley and Arrow-

Fig. 5 The tangential curvature map shows the morphostructural lineaments extracted (*black lines*) and their relative frequency distribution (*rose diagram*)
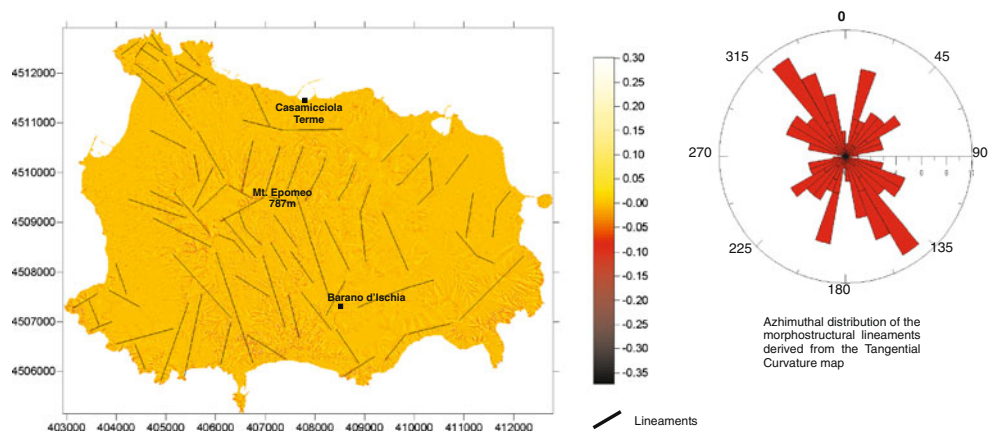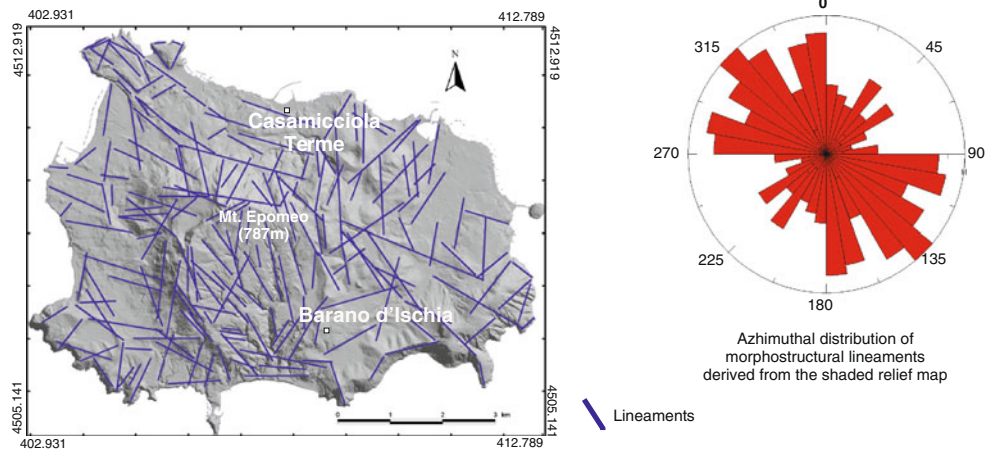
Fig. 6 The *shaded* relief map shows the morphostructural lineaments extracted (*blue lines*) and their relative frequency distribution (*rose diagram*)

smith (2000) (modified), which is described in the flowchart of Fig. 7a. We have removed all pits from DEM using Arc/INFO "fill" command before applying the algorithm, since the reliability of the topographic residual map depends fairly strongly on data quality. The high values of the topographic residual surface showing linear continuity have been used to extract the morphostructural lineaments whose statistical distribution has been calculated (Fig. 7b).
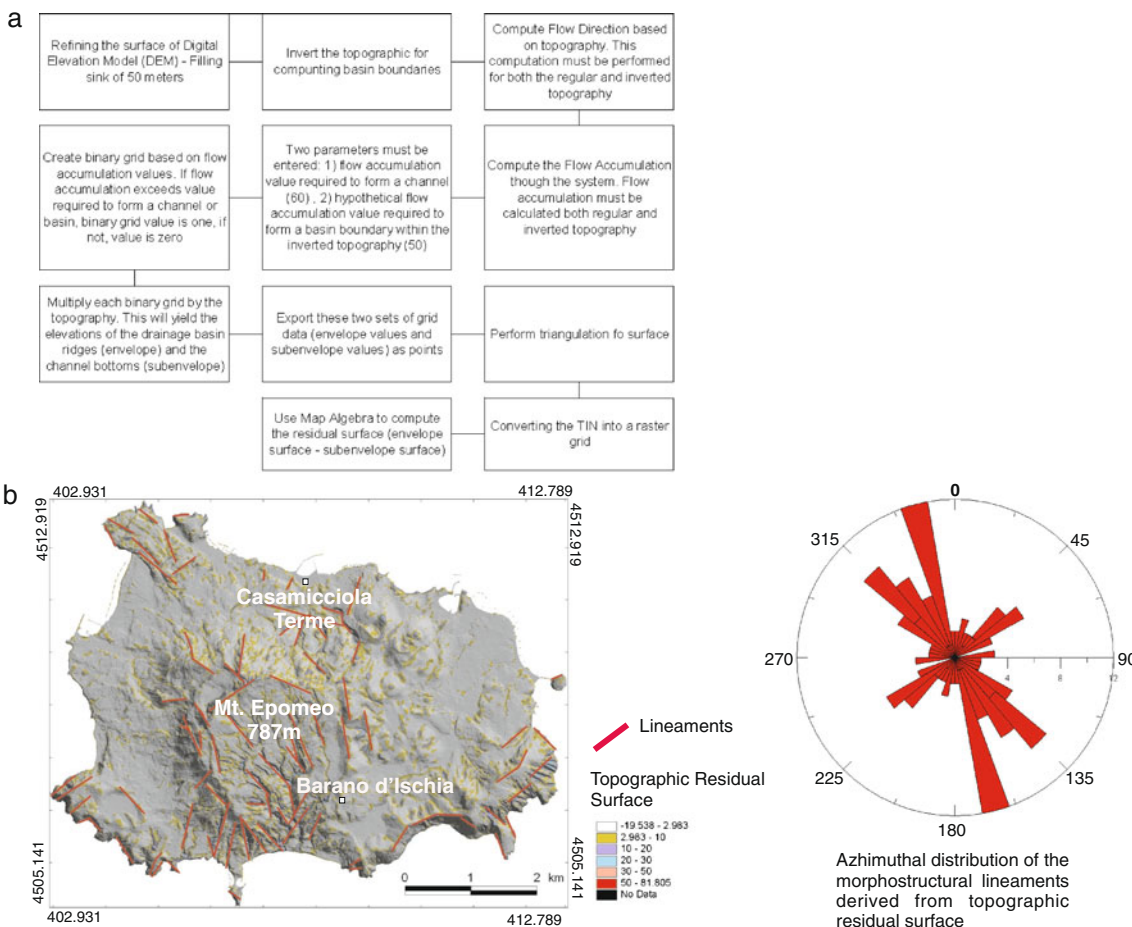

Fig. 7 The flowchart relative to the algorithm modified from Hilley and Arrowsmith 2000 (**a**); the topographic residual surface map with the morphostructural lineaments extracted (*red lines*) and the relative frequency distribution (*rose diagram*) (**b**)

Results of analysis

The different terrain parameters we analyzed allowed us to identify the morphostructural features of the Ischia Island as well as to validate these methods using structural mapping (Tibaldi and Vezzoli 2004; Chiodini et al. 2004; Foglio CARG 2010). The terrain slope values show that landslide scarps are prevalent on the N and NW side of the Mt. Epomeo and in the S-oriented fluvial valley. Additionally, crater rims on the NE and SE sectors of the island are highlighted by slope. Finally, morphostructural lineaments with NW–SE- and WNW–ESE-preferred distributions appeared in this analysis (Fig. 4).

The terrain aspect highlighted a main direction NW–SE and a secondary direction NE–SW relative to the crest line continuities. The analysis of the morphostructural lineaments derived from tangential (Fig. 5) and profile curvature calculations shows a preferred NW–SE and NNE–SSW orientation. These lineaments are consistent with those derived from the shaded relief map and are characterized by prevalent NW–SE, WNW–ESE, and NNW–SSE azimuthal distributions (Fig. 6).

The structural lineaments extracted from the topographic residual surface are concentrated both in the northern and in the southern flanks of Mt. Epomeo and in the NW corner of the Ischia Island (S. Montano Bay; Fig. 7b). Particularly in the southern flank, high values of topographic residual surface correspond to deep incisions and numerous debris flows reported by Tibaldi and Vezzoli (2004). The morphostructural lineaments are lacking in the eastern sector of the island where most morphological features are represented by young and small volcanic cones, craters, domes, and lava flows (Fig. 2).

The analysis of the azimuthal distribution of the lineaments extracted from the topographic residual surface has shown two preferred orientations: NNW–SSE and NW–SE (Fig. 7b). We have focused our study on the lineaments extracted from the topographic residual surface parameter because this parameter represents the real relief in a landscape and high values of it could correlate with rapidly uplifting areas that could identify as the active fault footwalls (Hilley and Arrowsmith 2000). Therefore, with the aim of verifying the current activity of the above morphostructural lineaments, we have compared their location with the distribution of the historical earthquakes epicenters (Fig. 8b), where it can be observed that the lineaments on the northern flank are closely associated with the location of the 1762, 1796, 1828, 1881, and 1883 historical earthquakes (Working Group 2004) and with the location of about 80 events that occurred from 1557 to 1995, found in the historical chronicles (Fig. 8b) (Alessio et al. 1996; Violante et al. 2003). Moreover, a density map of the occurred earthquakes has been carried out and overlapped on a sketch of the Ischia Island ortophoto (pixel 1 m) from Compagnia Generale Ripreseaeree, airborne 2000 to provide a correlation with the urbanization density, as a preliminary contribution to the seismic risk assessment of the Ischia Island (Fig. 8d). The point density tool (ArcGIS, ESRI) has been used for calculating the density of earthquakes epicenters passing through a circular neighborhood (250 m radius) of each output grid cell (cell spacing 50 m). The values of the density map have been classified in low density (1–10), medium density (10–30), and high density (30–60), where the maximum value corresponds to the maximum number of seismic events passing in that specific neighborhood (250 m radius). This derived map shows a clear coincidence among historical earthquake locations, morphostructural lineaments, and highly urbanized areas between Casamicciola and Lacco Ameno towns (Fig. 8d).

Conclusions

In this paper, we have produced a high-resolution DEM of the Ischia Island, which provides a basis for a digital terrain analysis. We extracted geomorphic metrics from the DEM to understand the recent tectonic processes of the study area and explore seismic risks posed by structures in this region.

The different terrain parameters were filtered to isolate long-wavelength characteristics of these data, and these images were classified. The terrain slope, terrain aspect, profile curvature, and tangential curvature identified lineaments and morphological features; on the other hand, the topographic residual surface identified morphostructural lineaments characterized by recent activity. Moreover, the original morphostructural data have been interpreted with the local seismic activity and the distribution of mapped structures and surface processes acting within the Ischia Island.

The results of our study have confirmed that many lineaments extracted from the terrain parameters are comparable with the tectonic lineaments reported in the literature (Fig. 8a, c) (Vezzoli 1988; Alessio et al. 1996; Acocella and Funiciello 1999; Molin et al. 2003; Chiodini et al. 2004), providing some validation of presented methodology. The statistical analysis of the spatial distribution of the lineaments extracted from all morphometric parameters shows three main orientations (NW–SE, NE–SW, WNW–ESE) corresponding to the main valley, ridgeline, and slope-break orientations of the study area. According to these results, it could be inferred that the morphological evolution of the Ischia Island has been conditioned by the regional extensional tectonics; such tectonics has been responsible for the Plio-Quaternary evolution of the Campania margin (Fusi et al. 1990,
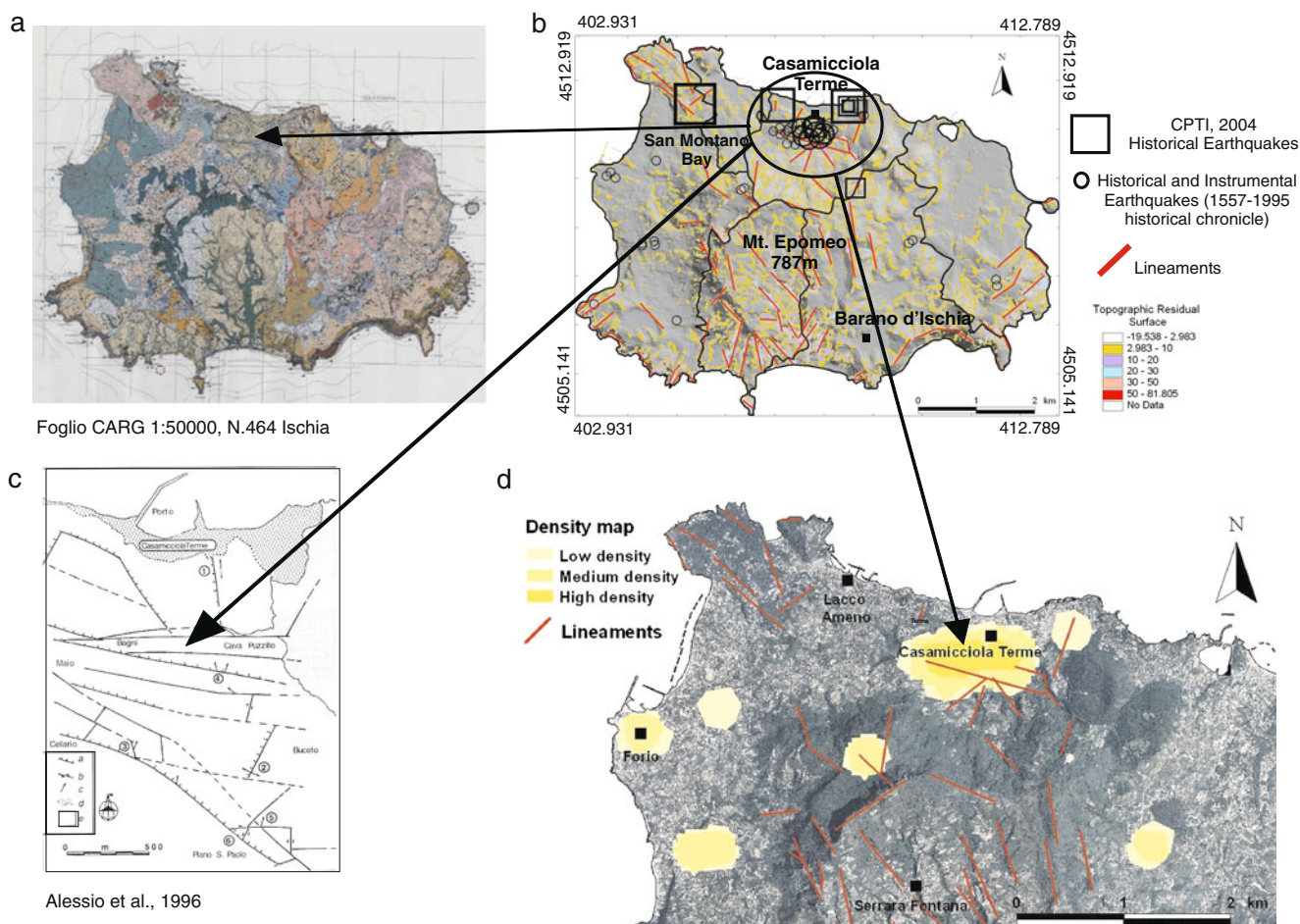
Fig. 8 **a** The geologic map of Ischia from Foglio CARG (2010); **b** Morphostructural lineaments of the Ischia Island, extracted from topographic residual surface, together with the historical and instrumental earthquakes: The *black ellipse* shows the correlation area of the morphostructural lineaments, seismicity, and faults from literatures; **c** structural sketch of the northern sector of the Island from Alessio et al. 1996; **d** density map of historical and instrumental earthquakes overlapping on a sketch of the Ischia Island ortophoto (pixel 1 m, CGR 2000) and the morphostructural lineaments extracted from the topographic residual surface (*red lines*)

Acocella and Funiciello 1999), and it is characterized by NE–SW-oriented extensional deformation, as also revealed by the most recent local tectonic structures (Malinverno and Ryan 1986).

Many of the extracted structural lineaments can represent fracture zones due to magma rising or due to gravitational instability or to faults not currently active. However, the main outcome of this paper is our interpretation of the morphostructural lineaments extracted from the residual topographic surface values in terms of recently active sources, as a contribution to assessment of seismic hazard of Ischia Island. The spatial distribution of the historical strong and moderate seismic events (Fig. 8b) shows an alignment WNW–ESE parallel to the northern coast of the Ischia Island, which is coherent with the direction of the extracted morphostructural lineaments (Fig. 8b). Therefore, we have correlated the extracted lineaments with the strong

historical earthquakes location (1762, 1796, 1828, 1881, 1883, Gruppo di Lavoro CPTI 2004) and with about 80 low-energy earthquakes location chronicled historically, which occurred between 1557 and 1995 (Fig. 8b) (Alessio et al. 1996, Violante et al. 2003). Such lineaments have been mapped (Fig. 8a, c) (Vezzoli 1988; Foglio CARG 2010), but they have never been recognized as causative faults of major and moderate seismicity. Therefore, we conclude that the urbanized area between Casamicciola and Lacco Ameno towns may be at risk due to the local concentration of both seismicity and active morphostructural lineaments. This is clearly shown by the density map of the occurred earthquakes which has been overlapped on the Ischia Island ortophoto (Fig. 8d).

Our research has demonstrated that this kind of methodology may provide information that may be used to characterize the neotectonic activities and risks associated

with this area. The metrics extracted from the topography are consistent with the most reliable literature data, providing some validation of our approach. Based on our experience, we speculate that the metrics produced by this technique might be similarly utilized in remote areas where field survey is impossible.

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