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Digital orographic map of peninsular and insular Italy

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Abstract

This paper describes method and contents of the digital orographic map of peninsular and insular Italy, comprising the islands of Elba, Sicily and Sardinia at 1:1,250,000 scale. The map was obtained using a modification of a previous proposal to define mountain orders, starting from the SRTM-NASA digital elevation model (90×90 m cell). The method, comparable to the well known drainage network ordering system, uses the topographic concepts of key contour, key saddle, summit point, prominence, and others. It was implemented in a step-by-step GIS-based procedure in order to automatically identify, delimit and order mountains and hills. The procedure permits the derivation of the parent relationship between orographic entities and organizes the ordered mountains in an orographic hierarchy. The orographic mapping system is able to produce an orographic dataset from DEM's, organize orographic geodatabases and manage mapping tools in many research fields. The map here presented is particularly useful to support interdisciplinary studies in tectonic geomorphology, topo-climatology, regional hydrology and landscape ecology at national scale.

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1. Introduction

Mountains are recognized as land sectors with higher elevation and with more prominent geographic features than their surroundings (Goudie, 1985; Smith and Mark, 2001; 2003). Historically, the scientific disciplines studying mountains are *orography*, mountain qualitative description, and *orometry* or *mountain geomorphometry*, mountain quantitative measurement (Cayley, 1859; Von Sonklar, 1873; Penck, 1894; Peguy, 1942; Neuenschwander, 1944; Strahler, 1952; Pike and Wilson, 1971; Dinesh and Fatzil, 2007; Hengl and Evans, 2009).

In this paper, "orography" will be used in a broader geomorphological meaning, as the basic landscape spatial expression resulting from the balance between relief creation by constructive processes, due to volcanic activity or tectonic forces, and destructive geomorphic processes, induced by water and other exogenous agents (Caine, 1974), working over different spatial/temporal scales (Bishop and Shroder, 2004).

Many disciplines, such as topo-climatology (Bohner, 2006; Bohner and Antonic, 2009; Cuomo and Guida, 2010a), regional hydrology (Bloschk, 2002; Viviroli et al., 2003; Cuomo and Guida, 2010b) and landscape ecology (Klijn and Udo De Haes, 1994; Blasi et al., 2007; 2010), require objective and quantitative approaches to detect and map orography in order to support landscape analysis and modeling (Shroder and Bishop, 2004).

This paper illustrates the method used to define and map the bounded, nested orographic entities of peninsular and insular Italy and describes the resulting map and complementary insets.

Starting from the mountain ordering system proposed by Yamada (1999), the method extracts the order and the parent relationship of the ordered mountains (Maizlish, 2003; Bivouac.com, 2004; Chaudhry and Mackaness, 2008), from a 90 m cell grid digital elevation model (DEM) downloaded from CGIAR-CSI (http://srtm.csi.cgiar.org/).

The resulting orographic entities are hierarchically codified into an orographic taxonomy, corresponding to six nested orders and are shown on a general orographic map at 1:1,250,000 scale. At the bottom of the map, three orographic transects, each representative for the northern, central and southern Apennine, are shown. The left side bottom figures explain the general orographic concepts and entities, and the structure of the orographic database. The central bottom figure shows an application of the above concepts to a complex karst landscape of the Cilento Geopark (Italy). Finally, an extraction of the homogeneous orographic entities is shown on the right bottom corner of the map.

2. Study area

The Apennines chain, the "spinal column" of the Italian peninsula, is a segment of the circum-Mediterranean mountain system (Rosenbaum and Lister, 2002; Carminati and Doglioni, 2004). Geographically, it consists of parallel mountain ranges extending over ca. 1,200 km between the Cadibona Col, to the north, and the Calabrian-Lucanian border, to the south. The Apennines are generally divided into three sectors: northern Apennine, central Apennine and southern Apennine. Calabria is a geologically distinctive orogen with an active tectonic-induced orography (Bonardi et al., 2001). Sicily has a complex orography including a segment of the Calabria-Peloritani orogen in the NE, a segment of the Apennine-Maghreb Chain (Dewey et al., 1989), and the volcanic complex of Mt. Etna. Sardinia is an isolated "European" terrain, following the spreading and rotation of the Balearic and Tyrrhenian basins (Rehault et al., 1984). The main subdivisions of the circum-Mediterranean chain and the reference locations cited in the text are shown on the top right of the orographic map.

3. Concepts, Materials and Methodology

The method used to build-up the map is based on the use of orographic parameters, describing the mountain terrain "as a whole" (Ahnert, 1984): mountain prominence and order, and their relationships. Mountain prominence is a first-order derivative of elevation, representing the height above all surrounding terrains or the relative elevation of a summit (Press and Siever, 1982; Summerfield, 1991); more precisely, it is the elevation difference between a peak and the saddle (key saddle) connected to the lowest contour (key contour) that encircles it and does not have higher peaks (Chaudhry and Mackaness, 2008).

Mountain order, as proposed by Yamada (1999), is defined by the contour lines on a topographic map in which each mountain is represented as sets of closed contour lines. These sets include only a single closed contour line for each elevation "unless a saddle (or pass) that divides the mountain has a height that exceeds the contour interval" (Yamada, 1999). Thus, the closed contour lines form a set of concentric shapes. Starting from the summits, each set of contour lines defines a 1^{st} order mountain above a connected saddle or pass; two or more 1^{st} order mountains produce a 2^{nd} order mountain and so on. If the highest of the lower-order mountains are of level m, then the surrounding higher-order mountain, with a lower elevation than the m^{th} order mountain, is identified as an $m + 1^{th}$-order mountain (Figure 1).

The Yamada definition of mountain orders is similar and complementary to that defined for stream orders by Strahler (1952).

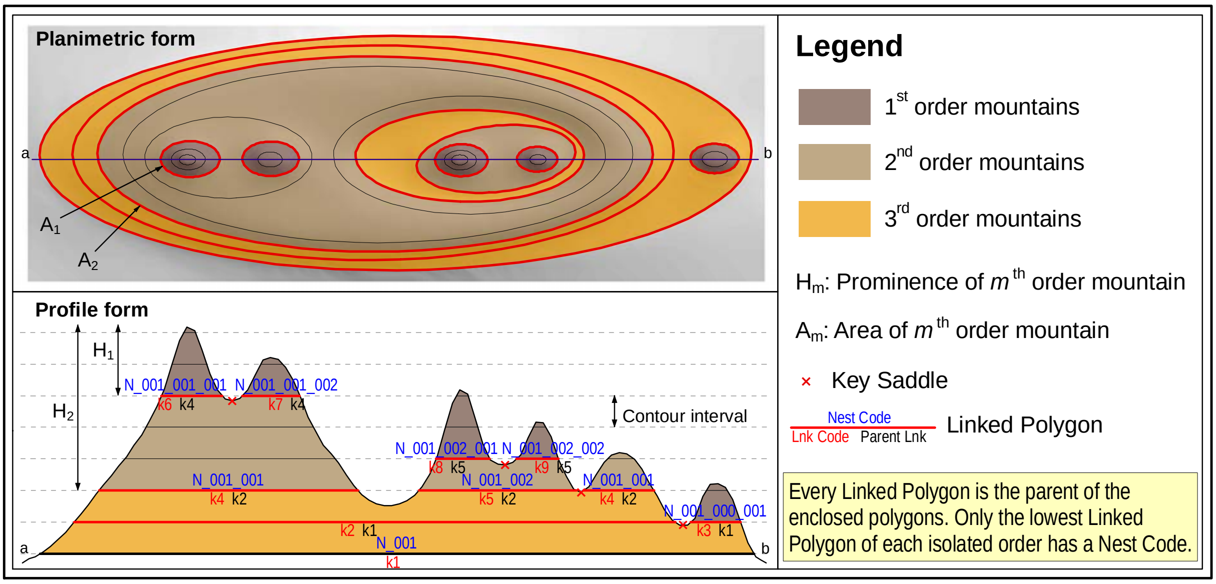


Figure 1. Scheme of order, prominence, area and parent relationship of the ordered mountains (mod. from Yamada, 1999).

The mountain-parent relationship established affiliation between topographic points, lines and polygons, relevant in mountain orography. Several definitions of the concept exist. Bivouac.com (2004) states that "the parent of each peak is the higher peak whose base contour surrounds the given peak and no other peak" and, thus, such a peak is referred to as the topographic parent. Other systems in defining parent peaks exist: "line parent" and "source parent". Both are used more often than the topographic parent (Maizlish, 2003). According to the previous definitions, the island parentage or encirclement parentage method (Molenaar, 1996; 1998; Van Smaalen, 2003; Chaudhry and Mackaness, 2008) was adopted to aggregate hierarchically nested mountain orders.

The main map, covering an area of 1,000,000 km^2, at 1:1,250,000 scale, is based on the CGIAR-CSI DEM (http://srtm.csi.cgiar.org/) with a 90 m horizontal resolution (Jarvis et al., 2006). To enhance the visual expression of the topography, a greyscale shaded relief map was produced and used as a background. From the same DEM a contour map with a 100 m contour interval was derived, as the appropriate value for the 1:1,250,000 scale and the selected cell size. Further map data, such as hydrography and main cities, were added from the "National Map Portal, Environment Ministry, Italian Government" (http://www.pcn.minambiente.it/). Other background images were obtained from the ArcGIS online map service (http://www.arcgis.com/).

The procedure here proposed starts from the Yamada (1999) mountain ordering proposal but, before ordering the mountains, it automatically provides the identification of those contour lines or groups of contour lines encircling any positive (mountains) or negative (depressions) orographic volumes, using and processing polygons instead of polylines.

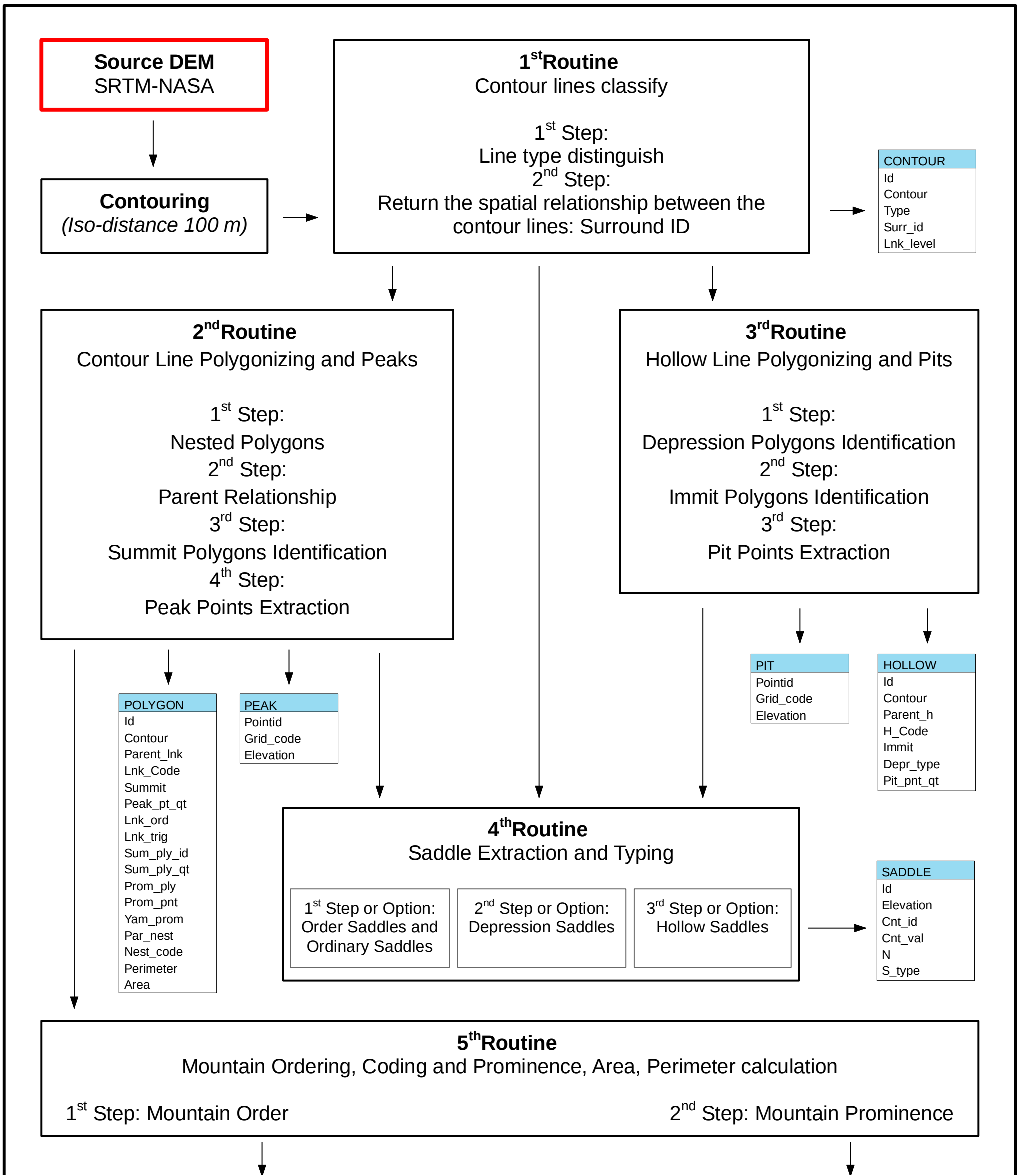
Based on the above background, concepts and materials, the applied methodology works as a GIS-based procedure, including five computer routines and several operational steps (Figure 2).

The first routine works on the polylines derived from the source DEM, starting with polyline pre-processing, providing the contour classification (Table 1) and then extracting the related contour lines table, comprising the contour line type, surrounding ID and the contour line level fields (Ackermann, 1978). The pre-processing routine is necessary first to identify the polyline surrounding all the "internal polylines". Thus, if for a generic contour value there are two contour lines one in the other (as in the case of a crater or volcanic rim), the procedure checks where the elevation value is greater than the contour value. If it happens inside the smallest contour lines, the geometry of the resulting polygon will coincide with the area encircled by the same polyline. On the contrary, if it happens in the area between the contour lines, the resulting polygon will have a complex geometry with a hole corresponding to the smallest polyline.

Type	Name	Definition
	Contour	A set of points having equal elevation above sea level.
Polyline	Contour line	An actual line drawn on a map, satisfying the above contour definition and having a value depending on the "contour interval" for the map
	Open contour	Open contour line with indefinite geographical extent for selected study area, not delimited as "island"
	Ordinary contour	Any closed contour line that surrounds an orographic volume
	Base contour	Ordinary contour not surrounded by any other ordinary contour
	Linked contour	Ordinary contour linked by key saddle
	Hollow contour	Closed contour line that doesn't surround an orographic volume
	Depression contour	Hollow contour not surrounded by any other hollow contour, but surrounded by another ordinary contour
	Base depression contour	Hollow contour not surrounded by any other closed contour line
	Surround Contour	Contour line that surrounds other contour lines with the same elevation value

Table 1. Polyline orographic entities.

The second routine performs polygon generation/classification (Table 2) and related polygon table manipulation, working in four steps: the 1st step consists in a nested polygonization of those contour lines surrounding an orographic volume; the 2nd step works on the previous nested polygons to construct the polygon parent relationships.



ID	CONTOUR	LNK_CODE	LNK_ORD	SUM_PLY_ID	SUM_PLY_QT	PEAK_PT_QT	PERIMETER	AREA	PROM_PLY	PROM_PNT	YAM_PROM
33487	500	k15903	6	15856	2800,00	2863,00	17117983,75	40696576242,54	2300,00	2363,00	2350,00
38878	0	k16	5	28780	1800,00	1820,00	1138541,11	24075308928,59	1800,00	1820,00	1850,00
38862	0	k3755	5	36417	3300,00	3313,00	1025884,39	25415189073,87	3300,00	3313,00	3350,00
11166	400	k14003	4	10517	1400,00	1469,00	222127,52	279871861,50	1000,00	1069,00	1050,00
13685	100	k7840	4	13287	600,00	619,00	175958,15	147563213,56	500,00	519,00	550,00
17794	300	k12628	4	13066	1700,00	1723,00	1932844,95	3868492020,09	1400,00	1423,00	1450,00
22132	200	k10594	4	21766	1500,00	1523,00	387005,30	706427413,83	1300,00	1323,00	1350,00
24418	500	k15782	4	23293	1500,00	1579,00	210086,38	233885484,94	1000,00	1079,00	1050,00
35631	300	k13262	4	34468	1900,00	1947,00	1212227,36	2657161219,03	1600,00	1647,00	1650,00
33487	500	k15903	4	15856	2800,00	2863,00	1225824,82	3383703965,42	2300,00	2363,00	2350,00
[illegible]	0	k7118	[illegible]	[illegible]	[illegible]	[illegible]	29408,84	[illegible]	[illegible]	[illegible]	550,00
38899	[illegible]	[illegible]	3	26423	500,00	[illegible]	[illegible]	[illegible]	500,00	557,00	[illegible]
38915	0	k7142	3	13490	900,00	989,00	119440,97	224002612,47	900,00	989,00	950,00

Figure 2. Flow chart of the adopted procedure, with routines, operational steps and related orographic database table.

Type	Name	Definition
Positive Polygon	Ordinary polygon	Polygon that contains only points with elevation value greater than its contour value
	Base polygon	Ordinary polygon not included in any other ordinary polygon
	Linked polygon	Ordinary polygon linked by a key saddle
	Order polygon	Linked polygon that causes an increase in the mountain order
	Summit polygon	Ordinary polygon that doesn't contain any other ordinary polygon

Table 2. Positive polygon orographic entity, name and definition.

In other words, once the procedure has derived the polygon set, it identifies all the polygons that are not encircled by any other polygon, calling them base polygons and, starting from these, it derives the parent relationship. Adopting a bottom-up procedure, any specific base polygon is the parent of all the enclosed polygons; if out of all these there are two or more polygons at the same elevation, the procedure marks them as linked polygons. At this point, the procedure considers these polygons, as the parents of all the enclosed polygons, until there are again more than one polygon at the same elevation. The 3rd step extracts the summit polygons from above nested polygons, identifying the polygon that doesn't have any other polygon included. The 4th step localizes and extracts the summit or peak points within the summit polygons and creates the table of the peak points, as the points with highest elevation within a summit polygon (within a first order mountain). The 3rd routine manages the same steps for those contour lines that don't surround an orographic volume, identifying the hollow contour polygons and depression polygons, to recognize immit polygons and, finally, to localize and extract the immit or pit points within the immit polygons and creating the pit points table.

Type	Name	Definition
Negative Polygon	Hollow polygon	Polygon that contains only points with elevation value lower than its contour value
	Depression polygon	Hollow polygon not included in any other hollow polygon, but included in another ordinary polygon
	Base depression polygon	Hollow polygon not included in any other polygon
	Immit polygon	Hollow polygon that doesn't contain any other hollow polygon

Table 3. Negative polygon orographic entities.

By means of the 4th routine, many types of saddle points were localized and extracted (Table 4).

Finally, the 5th routine derives the mountain orders from the polygon theme and calculates the prominences (Table 5). This routine assigns the nest code only to those linked

Type	Name		Definition
Point	Key Saddle	Ordinary saddle	Saddle connecting linked polygons
		Order saddle	Saddle connecting order polygons
	Depression saddle		Any saddle connecting depression polygons or connecting the depression polygons on the whole and their surrounding contour line
	Hollow saddle		Saddle connecting hollow polygons

Table 4. Point orographic entities.

polygons ranked as mountains that are the lowest linked polygons of each isolated order.

Name	Definition
Summit point elevation (PEAK_PT_QT)	Elevation value of the summit point within each summit polygon
Summit polygon elevation (SUM_PLY_QT)	Elevation value of the summit polygon for each linked polygon
Summit Point Prominence (PROM_PNT)	Prominence relative to the summit point for each linked polygon
Summit Polygon Prominence (PROM_PLY)	Prominence relative to the summit polygon for each linked polygon
Yamada Prominence (YAM_PROM)	Difference between summit polygon elevation + 0.5 contour interval – linked polygon elevation

Table 5. Name, code and definition of the mountain prominence calculated by the 5^{th} routine.

In order to validate the above procedure in a landscape containing most of the orographic entities above described, a orographic map of karst landscape of the Alburni Mts. (Aloia et al., 2010) was build-up at 1:5,000 scale (Figure 3 and inset in the main map bottom). This karst landscape was chosen because it is representative of the orographic conditions recurrent in the Apennine chain.

4. Results

The procedure above described is a general purpose, GIS-based mapping system suitable for quantitative orographic analysis, as a primary step in multiscale and interdisciplinary landscape studies.

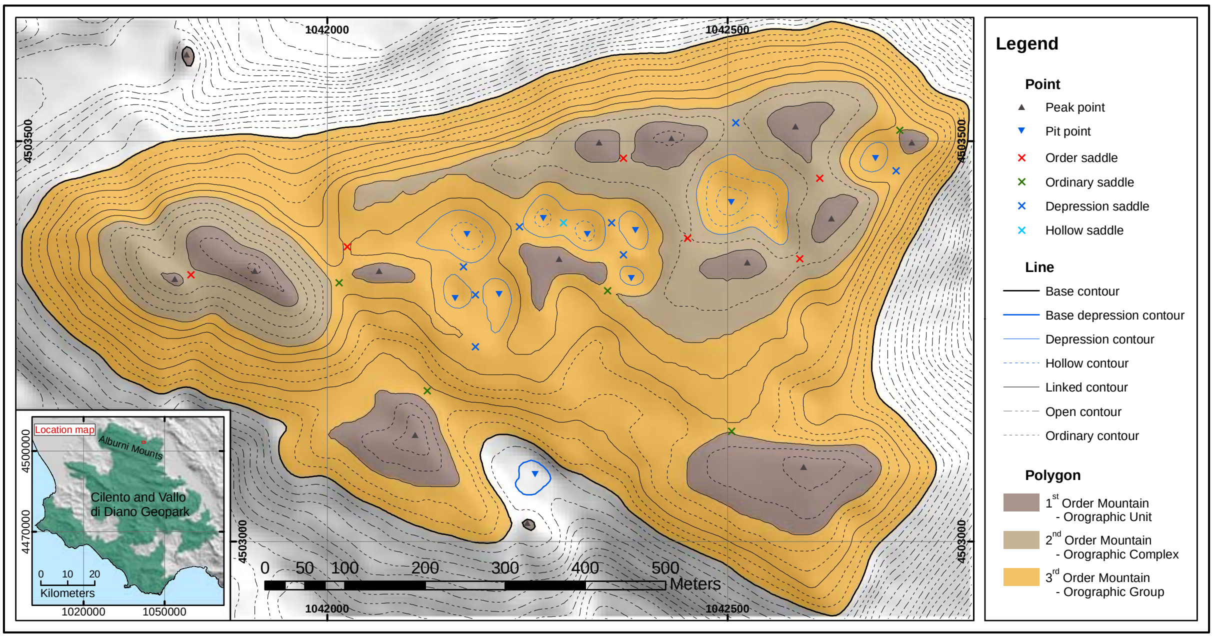


Figure 3. Orographic entity identification in a typical karst landscape (Alburni Mts – Cilento Geopark, Southern Italy).

As preliminary application, the procedure produced the "Orographic map of peninsular and insular Italy", composed of the following map insets, profiles, diagrams, tables and legends:

1. study area map, placed at the top right of the sheet, showing the locations and surrounding geo-structural setting;
2. orographic map (1:1,250,000 scale), showing the graphical results of the above applied methodology and procedure, as nested and isolated orographic entities. On the map are also shown the peaks with prominence higher than 1000 m (Appendix A);
3. transects of the ordered mountains across three representative profiles of northern, central and southern Apennines;
4. scheme and table of the nested and hierarchic orographic entities used in the map building procedure;
5. structure of the orographic relational database;
6. application of the procedure to a "training area": Mts. Alburni (Cilento and Vallo di Diano Geopark, southern Italy), a mountain karst landscape, containing all the orographic entities managed by the mapping system;
7. map of the homogeneous orographic entities.

To demonstrate the reliability of the orographic map system with regional geology and geomorphology, a spatial analysis on the hierarchical entities of the Apennine Chain (6^{th} mountain order) was performed, extracting their nested and non-nested 5^{th}, 4^{th} and 3^{rd} order mountains, respectively, and classifying them in point prominence classes (Figure 4).

An interesting graphical and conceptual result is the consideration that the sequence of orders 1-6 is not necessarily complete, but, in analogy with the hierarchical anomaly of the drainage network, some orders are 'skipped', like first order streams being tributary to a fifth-order river. For instance, many of the 4^{th} and 3^{rd} order mountains along the southern Tyrrhenian Borderland (see Cilento Geopark mountains) are part of the whole Apennine chain, but not of the southern Apennine chain, according to ongoing landscape eco-regional research (Blasi et al., 2010). Therefore, the authors propose a hierarchical taxonomy of the Apennine mountain orders organized in orographic entities (Table 6), modified from Cuomo and Guida (2010a). The validation of the above proposal, will be achieved in comparison with the results from ongoing orographic analysis at the European scale.

5. Conclusions

The orographic map of peninsular and insular Italy here presented is the first cartographic result of a GIS-based procedure to define the orographic map system (OMS), aimed at performing an objective approach in the identification, delimitation and characterization of mountain landscapes. Starting from previous proposals, OMS is an original tool developed to improve orographic understanding in landscape and environmental studies, integrating traditional and innovative geomorphometric approaches and interdisciplinary researches (e.g. TOPOMOD; http://www.topomod.eu/). The orographic entities extracted for the Campania region, were applied in regional topo-climatology (Cuomo and Guida, 2010b) to point out the role of regional scale orographic barrier in controlling the distribution, frequency and intensity of extreme local orographic precipitation (Rossi et al., 2005). The orographic groups and ranges are currently used in Blasi et al. (2010), as the orographic signature of relief in ongoing eco-regional research at a national scale.

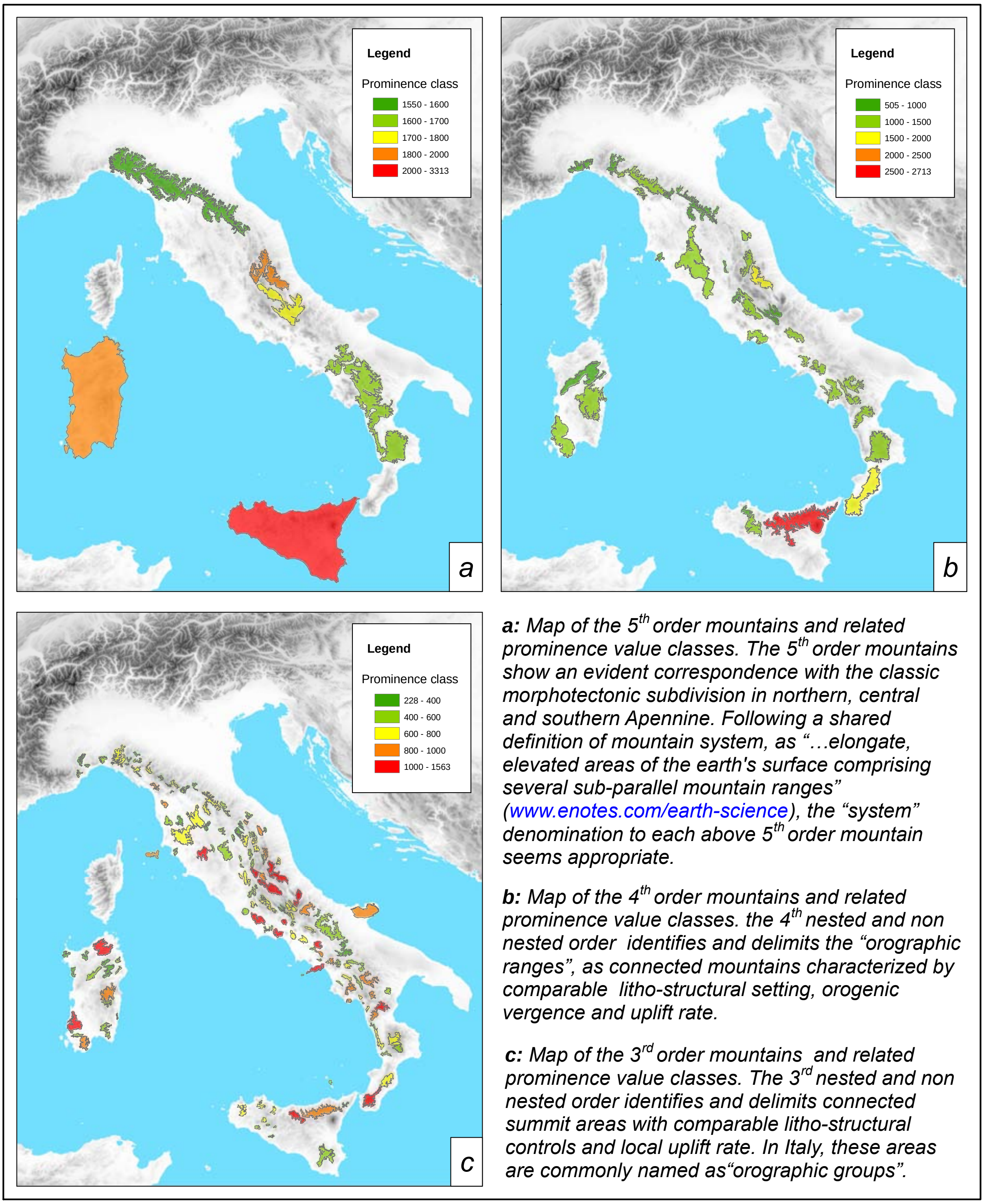


Figure 4. Maps of the high ordered mountains and related prominence value classes.

Mountain order	Orographic entity	Orographic and geological definition	Example
8	Orogen	An extensive belt of rocks deformed by orogeny, associated in places with plutonic and metamorphic rocks.	Alpine-Himalayan
7	Belt	Typically thousands of kilometres long and hundreds of kilometres across and parallel continental coastlines or margins.	Alps-Apennines
6	Chain	A set of mountain systems, grouped together for geographical, i.e. continuity/ mean relative relief and geological reasons, i.e. continental orogenetic style, timing and uplift rates. At least two orographic systems linked by a system key saddle.	Apennines-Maghreb
5	System	A group of mountain ranges tied together by common geological features. At least two orographic ranges linked by a range key saddle.	Apennines
4	Range	A mountain range is a single, large land mass consisting of a succession of mountains or narrowly spaced mountain ridges, closely related in position, direction, formation, and age. A component part of a mountain system or a mountain chain. At least two orographic groups linked by a group key saddle.	southern Apennine
3	Group	At least two orographic complexes linked by a complex key saddle.	Cilento Borderland
2	Complex	At least two orographic units linked by a unit key saddle.	Alburni Mts.
1	Unit	Peak area inside summit polygons without saddles .	“Figliolo”

Table 6. Proposal for the orographic entity hierarchy related to mountain order (modified from Cuomo and Guida, 2010a).

Software

The map and related database were collected, managed and processed using ESRI ArcGIS. A geo-referenced database,organized in shapefiles, is listed in Appendix A.

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Appendix A. Orographic data of the ordered mountains with a summit point prominence above 1000 m

Peak name[2]	Hierarchical orography–geological correspondence[3]	Geographical Coordinates	Elevation[4] (m asl)	Lowest LNK_CODE[5]	Lowest LNK_CODE Elevation[6] (m asl)	Lowest LNK_CODE Order[7]	Prominence[8] (m)
M. Cimone	Cimone Group - Tuscan-Emilian Range. **The Highest peak of the Nortern Apennine System**	44°11′38″N 10°42′05″E	(2165) 2150	k17439	600	5	1550
M. Pisanino	Apuane Range Northern Tyrrherian Borderland System	44°08′01″N 10°12′52″E	(1946) 1895	k21429	800	4	1095
M. S. Vicino	Umbria-Marche Range Central Apennine System	43°19′51″N 13°03′43″E	(1479) 1469	k14003	400	4	1069
M. Amiata	Amiata Group Southern Tuscan Anti-Apennine Range	4°54′N 13°38′E	(1738) 1723	k12628	300	4	1423
M. Vettore	Vettore Group - Sibillini Range Central Apennine System	42°49′N 13°16′E	(2476) 2461	k24728	1100	4	1361
M. Gorzano	Gorzano Group - Laga Range Central Apennine System	42°37′04″N 13°23′47″E	(2458) 2435	k26516	1300	3	1135
M. Terminillo	Terminillo Group - Reatini Range Central Apennine System	42°28′25″N 12°59′51″E	(2217) 2194	k24729	1100	3	1094
Corno Grande	Corno Grande Group Gran Sasso Range. The highest peak of the Central Apennine System and Apennine Chain	42°28′9″N 13°33′57″E	(2912) 2863	k15903	500	6	2363
M. Velino	Velino Group - Velino Sirente Range Central Apennine System	42°08′50″N 13°22′53″E	(2486) 2459	k25657	1200	3	1259
M. Amaro	Amaro Group - Majella Range Central Apennine System	42°03′N 14°03′E	(2793) 2777	k23554	1000	5	1777
M. Viglio	Viglio Group - Cantari Range Central Apennine System System	41°53′04″N 13°22′25″E	(2156) 2139	k20943	800	4	1339
M. Semprevisa	Semprevisa Group – Lepini Range Tyrrherian Borderland System	41°34′00″N 13°04′00″E	(1536) 1524	k14377	400	3	1124
M. Cairo	Cairo Group Southern Central Apennine System	41°32′31″N 13°45′36″E	(1669) 1660	k17444	600	3	1060
M. Miletto	Miletto-Matese Group Southern Apennine System	41°40′00″N 14°40′00″E	(2050) 2031	k20944	800	4	1231

M. Petrella	Petrella-Aurunci Group Southern Tyrrherian Borderland	41°19′00″N 13°39′00″E	(1533) 1523	k10594	200	4	1323
M. Camposauro	Taburno-Camposauro Group Southern Apennine System	41°06′30″N 14°36′30″E	(1390) 1384	k12818	300	3	1084
M. Limbara	Limbara Group Sardinia Block System	40°50′59″N 9°10′31″E	(1362) 1347	k980	300	3	1047
M. Avella	Partenio-Avella Range Southern Apennine System	40°58′49″N 14°41′04″E	(1598) 1579	k15782	500	4	1079
Vesuvio	Somma-Vesuvius Volcano Complex Tyrrherian Borderland System	40°49′18″N 14°25′34″E	1258	k8441	100	2	1158
M. Cervialto	Cervialto-Picentini Range Southern Apennine System	40°46′54″N 15°07′50″E	(1809) 1800	k19525	700	4	1100
M. S.Angelo Tre Pizzi	S. Michele-S.Angelo-Lattari Group Tyrrherian Borderland System	40°39′00″N 14°30′00″E	(1444) 1399	k10724	200	3	1199
M. Cervati	Cilento Range Apennine Chain	40°16′00″N 15°28′00″E	(1898) 1887	k17441	600	4	1287
M. Sirino	Sirino-Lucanian Range Southern Apennine System	40°07′58″N 15°50′10″E	(2005) 1990	k22630	900	4	1090
P.ta La Marmora	La Marmora-Gennargentu Range Sardinia Block System	39°58′00″N 09°19′00″E	(1834) 1820	k16	0	5	1820
Serra Dolcedorme	Pollino-Calabria-Lucanian Range **The higest peak of the Southern Apennine System**	39°53′40″N 16°12′57″E	(2267) 2249	k17438	600	5	1649
Punta Perda Sa Mesa	Linas Group Sardinia Block System	39°26′54″N 08°37′57″E	(1236) 1216	k52	100	4	1116
M. Botte Donato	Sila Range Northern Calabria System	39°17′03″N 16°26′50″E	(1928) 1927	k19524	700	4	1227
Montalto	Aspromonte-Serre Range Southern Calabria System	38°09′33″N 15°55′14″E	(1955) 1947	k13262	300	4	1647
Pizzo Carbonara	Madonie Group Sicily Maghreb Range	37°53′39″N 14°01′31″E	(1979) 1967	k6263	800	3	1167
Rocca Busambra	Sicani Range Sicily Maghreb Range	37°51′20″N 13°23′50″E	(1613) 1601	k5620	600	4	1001
Etna	Etna Volcano Complex Sicily System	37°44′00″N 15°00′00″E	(3340) 3313	k3755	0	5	3313

Notes: [1]the mountain peaks are listed from north to south; [2]Main mountain peak denomination; [3]Hierarchical orography-geology (see Table 6); [4]Mean elevation in the cell; in parentheses, absolute elevation a.s.l.; [5]Code for the lowest "linked polygon" (Table 2). [6]Elevation of the lowest "linked polygon" (Table 2); [7]Order of the lowest "linked polygon" (Table 2); [8]Summit Point Prominence (Table 5).