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MORPHOMETRIC EVIDENCE OF THE TOPOGRAPHIC GROWTH OF THE CENTRAL APENNINES

ABSTRACT: MOLIN P. & FUBELLI G., *Morphometric evidence of the topographic growth of the central Apennines*. (IT ISSN 1724-4757, 2005).

On the basis of DEM analysis, we examine the tectonic geomorphology of the Apennines in central Italy to figure out the topographic evidence for how Apennines landscape was shaped by its emergence above sea level, in the tectonic context of a growing mountain chain. Geologic and geomorphic data suggest that its topographic growth was slow during the phase of crustal shortening (Miocene-Pliocene), but accelerated at the end of lower Pleistocene, when tectonics was already dominated by extension. Such different uplift rates should influence the development of the resulting landforms. We investigate the topography and the drainage features of a E-W transect across central Italy, focusing on topographic metrics, drainage pattern and stream long profiles. The results indicate that the Apennines topography is characterized by the superimposition of a short wavelength (10-30 km wide spacing), linked to local tectonic structures (extensional on the Tyrrhenian side and compressive on the Adriatic side), and a long one that corresponds to a broad topographic bulge 200-300 km wide, that records a regional uplift. As a response, the rivers incised the topography of the growing chain mostly the same and, interacting with climate changes, generated at least three major inset alluvial terraces. In particular, on the Tyrrhenian side, the rectangular drainage pattern indicates the strong influence of the extensional tectonics. This is also evident in the stream long profiles, where knickpoints and knickzones correspond with tectonic lineaments and extensional basins respectively. The hydrographic network draining to the Adriatic Sea shows a parallel pattern. The knickpoints of the stream long profiles generally correspond to rock changes and to very deep and narrow gorges, where the rivers incised the compressive structures reaching their cores. A high-resolution DEM of an area just south of Ancona provided information at a nested scale of observation. This region contains two major low relief surfaces. The one at higher elevations is located at the crest of the chain cutting across carbonates and marls. The other surface is inset into the flanks of the range and mostly cuts across turbidites. A third geomorphic surface, located more eastward, is underlain by Pliocene and Quaternary deposits. Coupling the morphometry analysis, the map of Pliocene-lower Pleistocene deposits, and previous studies, we explore the relationships among the landscape features, the regional vertical tectonism, and the local deformational processes. The results are consistent with a landscape dominated by the broad Quaternary uplift superimposed on local tectonics, suggesting new constrains for the long term evolution of the landscape of central Italy in the context of the Apennines topographic growth.

KEY WORDS: Morphometry, Uplift, Central Apennines.

INTRODUCTION

Topography is generated by the competition between tectonics that moves rock masses, and surface processes that are responsible for their redistribution and for the landscape shaping. Therefore, although variables such as climatic changes should be considered, landscape features, as surface elevation variations and drainage adjustments, can record landscape tectonic history. In this perspective, especially in tectonically active regions, the analysis of topography represents an important source of information on the long-term landscape evolution. In the framework of plate convergence, the relationship between crustal shortening and topographic growth is still a largely debated topic (Willett & *alii*, 2001). In the Apennines, the growth of topography was slow during the phase of major crustal shortening (Miocene-Pliocene), but strongly accelerated in the Quaternary, when the shortening slowed down and the tectonics was already dominated by crustal extension, (Dramis, 1992; Calamita & *alii*, 1999; Coltorti & Pieruccini, 2000). In the emergent chain, such different uplift rates should have influenced the development of landforms. Thus the topographic growth of the Apennines is a good working model that could provide the general topics of mountain chain uplift with new constraints. In this framework, we have investigated the topography and drainage features of a E-W transect across north-central Italy (Tuscany-Marche area), where previous studies provide a good background for discussing results. In particular, focusing on landscape morphometry, drainage pattern and stream longitudinal profiles, we tried to figure out the topographic evidence for

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how Apennines landscape was shaped by its emergence above sea level, in the tectonic context of a growing mountain chain. The goal of this paper is to explore the relationships among the landscape features, the regional vertical tectonism at a convergent margin that drive broad uplift, and the local deformational processes that induce adjustments of streams and drainage patterns. The results are consistent with a landscape dominated by the broad Quaternary uplift of the Italian Peninsula superimposed on local effects of tectonics, suggesting new constrains for the long term evolution of the landscape of the central Italy in the context of the Apennines topographic growth.

GEOLOGICAL SETTING

In the Mediterranean area, the Italian Apennines are a local expression of the convergence between the European and African plates. Between 30-35 My, as a consequence of a decrease of the northward relative motion of Africa, extensional tectonics generated a backarc basin (the present Ligurian-Provençal basin) and induced the orogenic wedge, previously formed by the north-dipping subduction zone along the southern margin of Europe, to move southeastward (Lonergan & White, 1997; Jolivet & Faccenna, 2000) (fig. 1a). This block remained on the southern margin of the backarc basin between 30 and 16 Ma and an accretionary prism (part of a new forearc high) developed in front of it (Malinverno & Ryan, 1986; Patacca & *alii*, 1990; Lonergan & White, 1997; Jolivet & Faccenna, 2000; Faccenna & *alii*, 2001). Around 15-10 My, extensional tectonics originated the opening of the Tyrrhenian backarc basin and initiated the eastward migration of the Apennines foredeep chain system (Malinverno & Ryan, 1986; Patacca & *alii*, 1990; Faccenna & *alii*, 2001) (fig. 1a). As the compressive front migrated eastward, on the western flank of the Apennines, extensional tectonics generated subsiding basins, separated by ranges following the NW-SE trend of the chain (fig. 1b). The sedimentation in the extensional basins, started in Late Tortonian-Messinian, had been strongly influenced by a NW-SE structural high called Middle Tuscany Ridge (Bossio & *alii*, 1993; Martini & Sagri, 1993; Bossio & *alii*, 1995). Indeed, west of the ridge, the basins were filled with continental and marine deposits, while east of it the sediments were exclusively continental (Bossio & *alii*, 1993; Martini & Sagri, 1993; Bossio & *alii*, 1995; Testa, 1995). After the Messinian salinity crisis, in the lower Pliocene, as a consequence of the marine ingression, the sedimentary environment in the extensional basins of both sides of the Middle Tuscany Ridge changed progressively from continental to marine, suggesting the ridge did not operate as a major barrier for this transgression (Bossio & *alii*, 1993; Martini & Sagri, 1993; Bossio & *alii*, 1995; Amanti & *alii*, 2003). Note that the fluvial deposits of lower Pliocene contain pebbles made up of eurite (Bossio & *alii*, 1993; Amanti & *alii*, 2003), a magmatic rock presently outcropping only in the Elba Island, suggesting that this area was already emerged, similarly to the above mentioned ridges.

In the lower Pliocene, on the Adriatic side, the foredeep deposits were progressively unconformably overlain by littoral sand and fluvial-delta polygenic conglomerate (Bigi & *alii*, 1995; Cipollari & *alii*, 1999). The features, shape, and evolution of these sedimentary cycles were controlled by the development of anticlines and thrusts (Calamita & *alii*, 1991; Bigi & *alii*, 1995).

In upper Pliocene-lower Pleistocene, the marine sedimentation persisted on both sides of the Apennines, even if with a progressive regression trend, interrupted by several erosion surfaces (Carboni & *alii*, 1994; Bigi & *alii*, 1995; Centamore & Nisio, 2003). Contemporary, the extensional tectonics progressively affected the chain, giving rise to intermontane basins (Calamita & *alii*, 1982; Dramis, 1992), partially filled by upper Pliocene-middle Pleistocene continental deposits (Cavinato & *alii*, 1994; Galadini, 1999).

During Quanternary, the Apennines were dominated by extension and by vertical movements (D'Agostino & *alii*, 2001, and reference herein). Indeed, starting at the end of lower Pleistocene, a significant uplift of the whole Apennines chain took place, inducing the complete emersion of the basins and the headward river incision, that often reached the intermontane basins incising their filling deposits (Ambrosetti & *alii*, 1982; Dramis, 1992; Ascione & Cinque, 1999; Calamita & *alii*, 1999; Coltorti & Pieruccini, 2000; D'Agostino & *alii*, 2001; Bartolini, 2003). In the Periadriatic sector, the uplift induced a progressive tilting to E-NE of the marine sediments and compressive structures lightly deformed the Plio-Pleistocene deposits (Calamita & *alii*, 1991; Bigi & *alii*, 1995; Centamore & Nisio, 2003).

Nowadays compressive weak seismicity continues in the eastern flank of the Apennines, whereas extension is active in the axial sectors of the chain (Gasparini & *alii*, 1988; Patacca & *alii*, 1990; Lavecchia & *alii*, 1994; Montone & Mariucci, 1999; Frepoli & Amato, 2000).

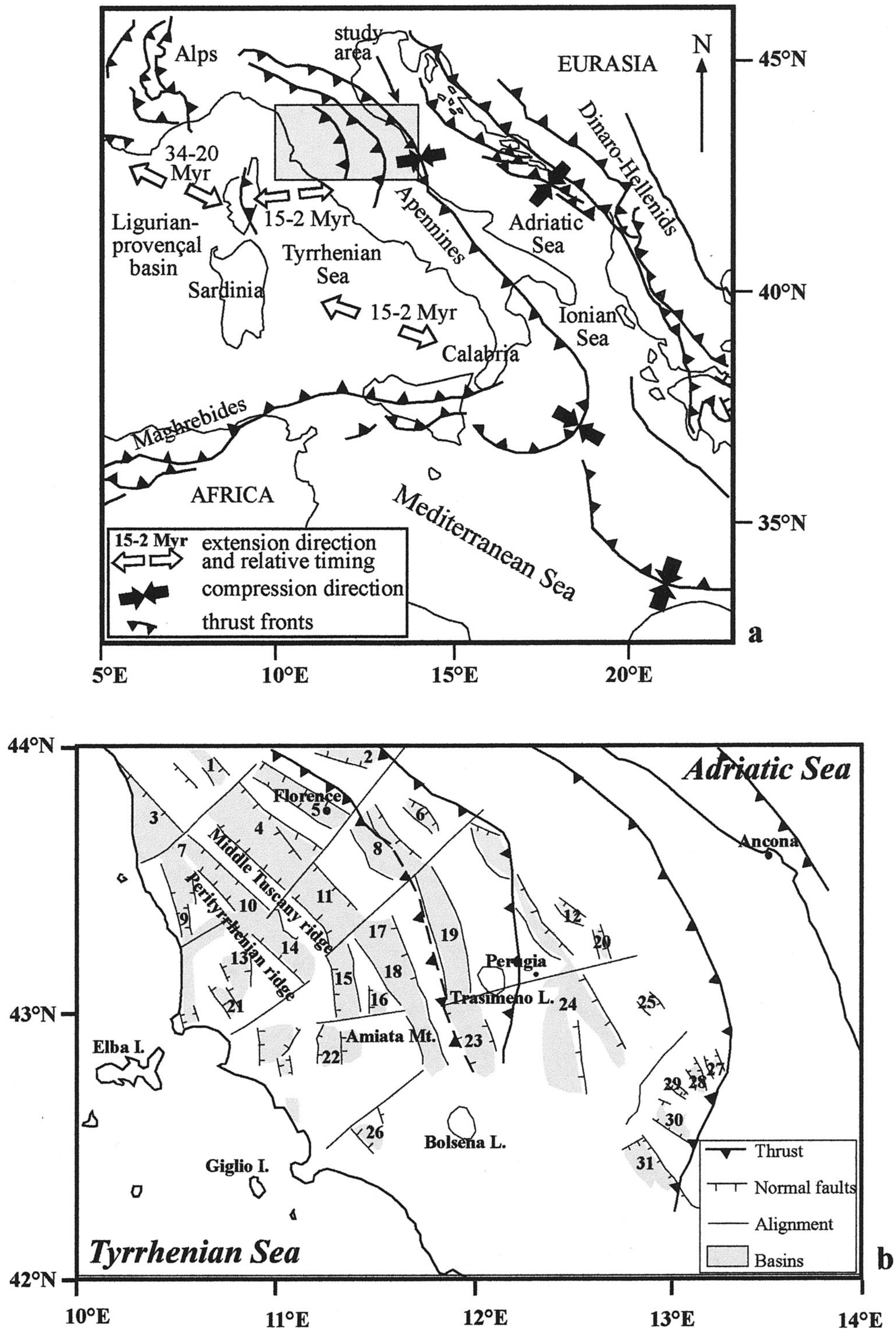
METHODS

This study analyzes landforms at a variety of scales designed to characterize both local and regional tectonic processes. The primary data source were a 90 m resolution DEM derived from the SRTM data and a ~250 m pixel size DEM provided by the APAT-Servizio Geologico. They are used for topographic cross-section, drainage pattern, and river longitudinal profile analysis. A secondary source is a 20 m pixel size DEM used to analyzed landforms at local scale.

Swath profiles and cross-sections

The 90 m resolution DEM have been sampled at regular intervals of longitude to generate two E-W oriented swath profiles. To produce these cross-sections, in an observation window with a length dimension equal to 4° of longitude and a width dimension equal to 1' of latitude, we calculated the maximum, minimum and mean eleva-

FIG. 1 - a) Simplified tectonic map of central Mediterranean (modified from Lonergan & White (1997)) and location of the study area. b) Generalized structural map of central Italy and location of the extensional basins (Martini & Sagri, 1993, modified). Basins: 1: Montecarlo; 2: Mugello; 3: Viareggio; 4: Elsa; 5: Florence; 6: Casentino; 7: Tora-Fine; 8: Valdarno; 9: Cecina; 10: Volterra; 11: Casino; 12: Gubbio; 13: Serrazzano; 14: Radicondoli; 15: Camigliano; 16: Velona; 17: Siena; 18: Radicofani; 19: Northern Val di Chiana; 20: Gualdo Tadino; 21: Montebamboli; 22: Baccinello; 23: Southern Val di Chiana; 24: Valle Tiberina; 25: Colfiorito; 26: Albegna; 27: Castelluccio di Norcia; 28: Norcia; 29: Cascia; 30: Leonessa; 31: Rieti.



tions for each interval of 3 arcseconds of longitude per 1' of latitude. The observation windows are oriented E-W to make data acquisition easier. The swath profiles, representing the trends of maximum, minimum and mean elevations and so, showing all the wavelengths of topography, allow to better evaluate which wavelengths are more suitable to explore the possible relationships between topography features and tectonics.

For both swath profiles, we also calculated the relief topography simply subtracting arithmetically the minimum elevations from the maximum ones. Generally speaking, the relief topography reveals where the landscape is deeply incised in a way that is not immediately obvious from the rough topography.

Since the E-W orientation of the swath profiles was not exactly perpendicular to the tectonic structure, it could influence the amplitude of the wavelength components of topography. To avoid this problem, we also extracted two cross-sections across the study area from the 250 m resolution DEM. These topographic profiles were oriented from NNE-SSW to NE-SW in order to be perpendicular to the main tectonic structures.

Stream longitudinal profiles

A stream longitudinal profile (long profile) is a plot of river length with respect to its elevation above sea level. We have generated long profiles for streams in central Italy, importing the 90 m and 250 m pixel size DEMs in the RiverTools software and extracting the stream network. In the process of the network extraction, the software fills all the sinks to generate a depressionless DEM, necessary to calculate the flow direction for each cell. A following routine uses the flow direction file to extract the hydrographic network. In this process, the software calculates also the drainage area relative to each generated stream reach.

Long profiles of alluvial channels and many bedrock or mixed-bedrock-alluvial channels are typically concave-up, a shape traditionally equated with a graded, equilibrium profile (Mackin, 1948; Pazzaglia & *alii*, 1998 and reference herein; Whipple, 2004). Deviations from this form may indicate that the fluvial system is in a transient state of adjustment to a base level, tectonic, climatic, or rock-type perturbation. In particular, convex segments called knickpoints or knickzones depending upon their length, can be investigated to evaluate their coincidence with tectonic perturbations at scales ranging from the whole chain to local structures.

To quantify the general shape of stream long profiles, we have measured the profile's concavity (the rate of change of profile curvature) through two different methods. In the first one, the concavity (σ) is calculated as the normalized area under the stream long profile (A_p) with respect to the area of a right triangle (A_{tr}) where the hypotenuse connects the divide to the mouth of the long profile (Demoulin, 1998):

$$\sigma = 1 - (A_p / A_{tr}) \tag{1}$$

In the second method, the concavity is calculated according to a power law relationship between the channel slope S and the upstream drainage area A (Hack, 1973; Snyder & *alii*, 2000; Whipple, 2004):

$$S = k_s A^{-\theta} \tag{2}$$

In the equation (2), the long profile concavity (concavity index) is θ and the channel steepness (steepness index) is k_s, the slope and the y-intercept respectively of a regression line through a log-log plot of the drainage basin area vs. slope. The concavity index, which values are independent from drainage basin size and shape, varies widely between 0.3 and 1.2, but it could be either negative or extreme (θ>1) (Whipple, 2004 and reference herein). In general, θ<0.4, 0.4-0.7, and 0.7-1.2 are associated respectively to low, moderate, and high concavities (Whipple, 2004). The channel steepness index, generalized form of the stream-gradient index (Hack, 1973), is influenced by the rate of rock uplift as well as by the rock-type (Snyder & *alii*, 2000; Duvail & *alii*, 2004; Whipple, 2004).

Low relief surfaces

In the study area, many Authors (Dramis, 1992; Calamita & *alii*, 1999; Coltorti & Pieruccini, 2000) reported on gently undulated low relief surfaces located in the mountain slopes and tops and interpreted as the remnants of old landscapes formed before the Quaternary uplift. The Authors themselves, during field investigations in central and southern Apennines, observed these low relief surfaces cutting across bedrock steep dipping strata and bordered by steep escarpments (Fubelli, 2004; Molin & *alii*, 2004). So, to get more detailed information on the Apennines long term landscape evolution, we used ArcGIS calculating tools to analyze a 20 m resolution DEM: we extracted surfaces characterized by very low slope values (less than 15° or 5°) and located on mountain and hill interfluves at elevation above 200 m.

MORPHOMETRY DATA

Swath profiles and cross-sections

To provide with information on the wavelength and amplitude of the topography of the Apennines mountain chain, we have analyzed two cross-sections passing across central Italy and two swath profiles, the northern one going from Livorno to Ancona and the southern one from the Elba Island to Ascoli Piceno (fig. 2).

The two cross-sections (fig. 3) are oriented perpendicularly to the trend of both main extensional and compressive tectonic structures. They show the central Apennines as a ~250 km wide asymmetrical mountain chain, roughly characterized by a steeper and shorter Adriatic flank and a wider and gentler Tyrrhenian slope. The asymmetry is well illustrated by the 4th order polynomial trend-line best fitting the cross-sections topography (fig. 3). We have chosen the 4th order polynomial because, removing the high frequency components of topography, it describes a wavelength coherent with the long one of the free air gravity anomalies of central Apennines (D'Agostino & *alii*, 2001).

The asymmetry of the chain appears as well in the maximum, minimum and mean elevations trends of the swath profiles (fig. 4). In the northernmost swath profile (fig. 4a), the much wider western flank is characterized by a sequence of basins and ranges from the Tyrrhenian coast up to the Mt. Acuto highest peak. These basins are depressions generated by the extensional tectonics that affects the western side of the Apennines. In the eastern flank,

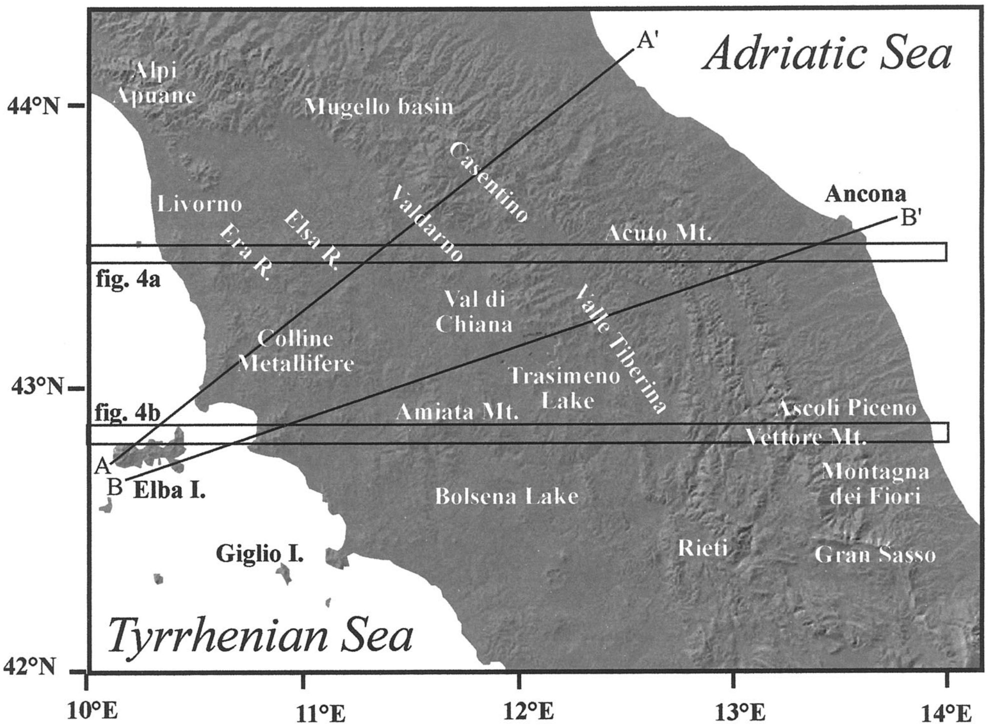


FIG. 2 - Digital topographic map of central Italy, showing the location of the cross-sections of fig. 3 and of the swath profiles of fig. 4.

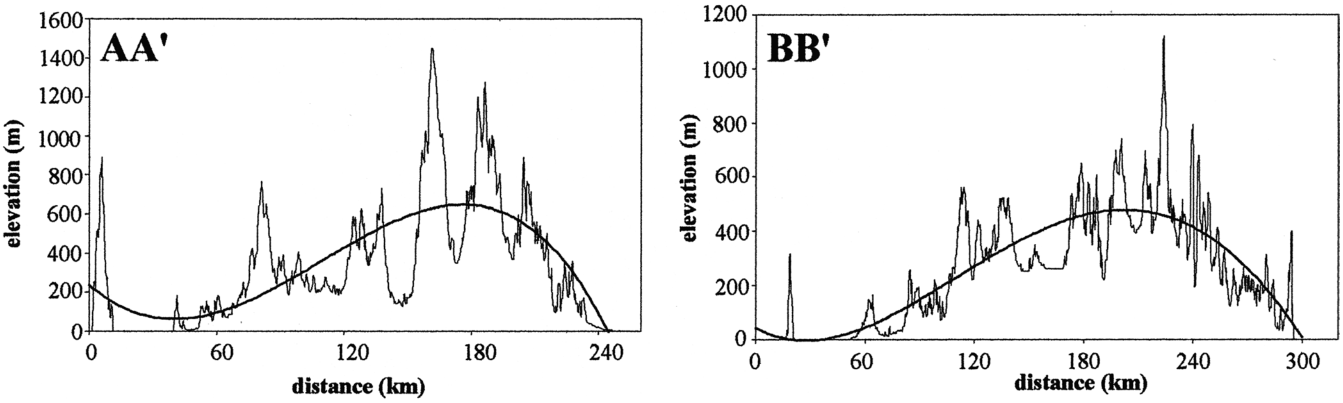


FIG. 3 - Cross-sections across central Italy (for location see fig. 2), roughly perpendicular to the regional tectonic structures. In the diagrams the polynomial 4th order trend-line best fitting the topography shows the asymmetry of the chain, characterized by a steep Adriatic flank and a much wider and gentle Tyrrhenian side.

topography decreases more regularly towards the Adriatic Sea. This decrease is interrupted by several troughs corresponding to compressive structures that thrusted marls and carbonates on turbidite successions.

The southern swath profile shows a topography trend similar to that of the northern one (fig. 4b), although the Mt. Amiata volcano interrupts the general shape of the western flank of the chain and the Mt. Vettore highest peak reaches a much higher elevation (~2400 m). Moreover the southern profile intersects the northern portion of Castelluccio intermontane basins, an internally drained depression located along the regional divide.

In the cross sections as well as in both swath profiles (fig. 4), the topography pattern appears to be the result of the superimposition of two main wavelengths. The short one is a 10-30 km spacing of troughs and ridges in the western flank of the chain. Note that in the southern profile, the Elba Island is part of the basin and range setting. In the eastern flank of the chain, the wavelength spacing becomes much shorter.

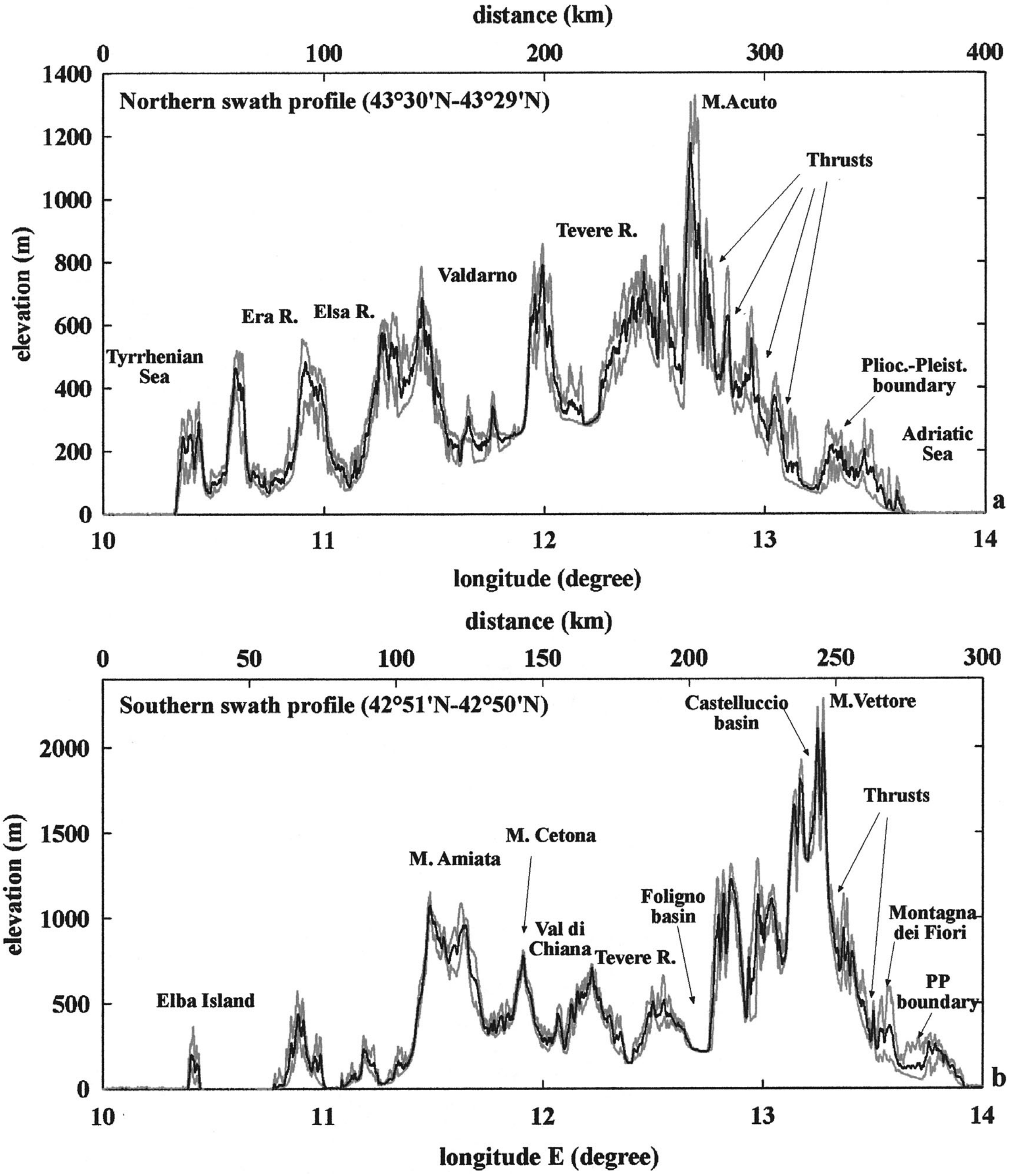
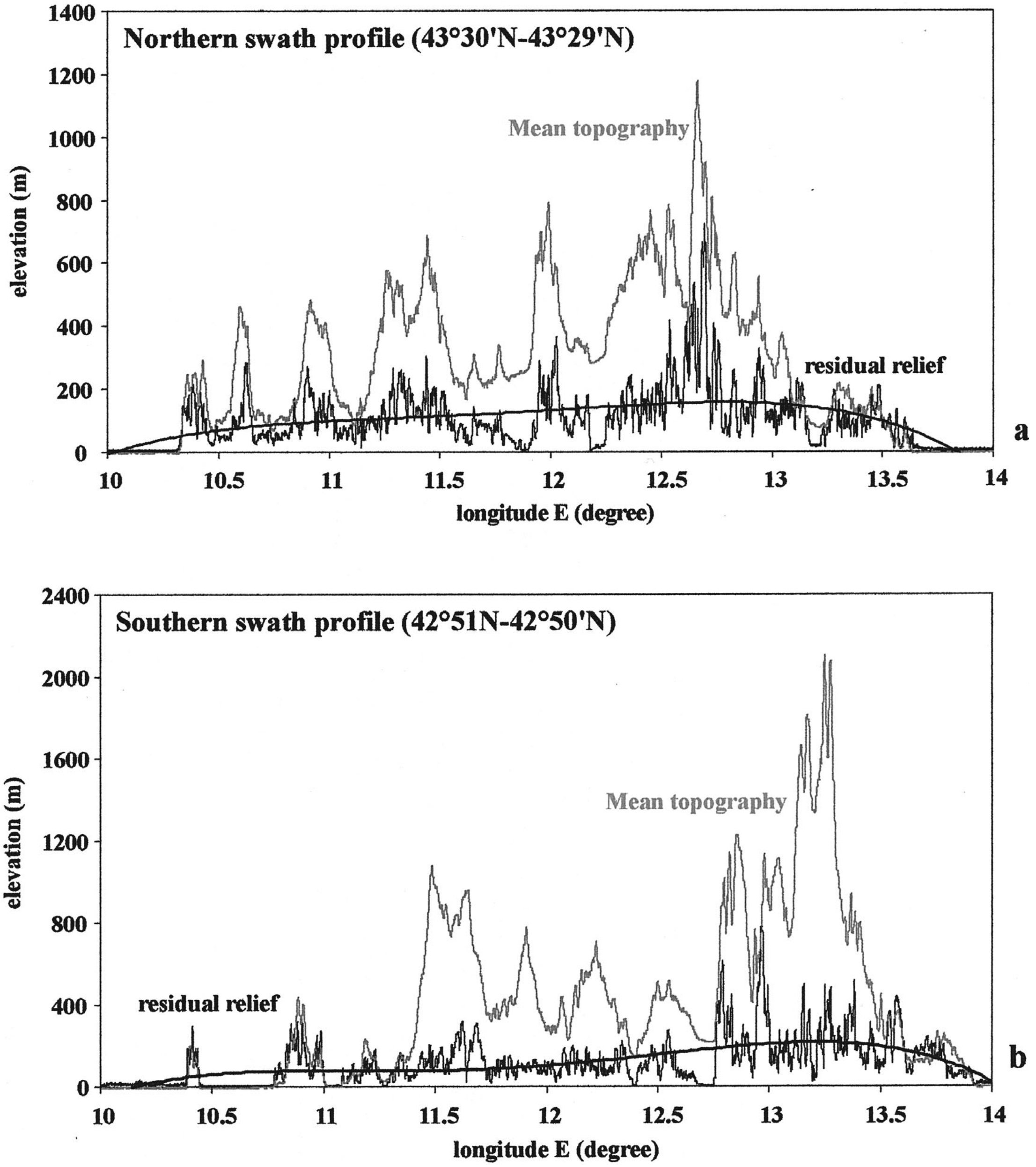


FIG. 4 - a, b) Maximum, minimum, and mean topography extracted from a suite of 21 adjacent cross-sections contained in a window with a length dimension equal to 4° of longitude and a width dimension equal to 1' of latitude. The location of the observation windows are reported in fig. 2. The swath profiles shows the Apennines topography as the result of the superimposition of two main wavelengths (see the text for explanation).

The second wavelength is much wider as compared with the short one. That is well evidenced, by the 4th order polynomial trend-line that best fits the elevation of the cross sections in fig. 3. Anyway, in these profiles, as well as in the swath ones (fig. 4), the long wavelength corresponds to a sort of broad topographic bulge (~250 km wide) that includes the whole Apennines chain. D'Agostino & *alii* (2001) obtained similar results studying swath profiles located more to the south and distinguishing two wavelengths of the same entities.

The elevation data of the swath profiles have been used to extract the relief (fig. 5) that, subtracting arithmetically the minimum topography from the maximum one, gives a general idea of the degree of landscape dissection. In general, both diagrams show a local relief that tends to maintain a more or less constant value, usually not exceeding 400 m. Just in correspondence with the highest peaks of the chain, it reaches an elevation of ~750 m, appearing to be independent from the very much different elevations reached by Mt. Acuto and Mt. Vettore (fig. 4). The more or less constant relief value is confirmed by the 4th order polynomial trend-line fitting it. This latter shows a relatively flat pattern (~200 m), and has a wavelength equal to the one fitting the mean topography of the Apennines chain.

FIG. 5 - a, b) Diagrams showing the relief (black line) computed by arithmetical subtraction between maximum and minimum elevation of the two swath profiles. The mean elevation (gray line) is also reported as a topographic reference. In both profiles the polynomial 4th order trend-line has a roughly flat shape, never exceeding the 200 m of elevation, suggesting the river incision is mostly governed by the long wavelength topographic bulge. In correspondence with the highest peaks of the chain, the relief reached in both cases 750 m, independently from the maximum elevation of topography.



Drainage pattern and stream longitudinal profiles

The features of the hydrographic network of the study area as well as that of the whole the Italian Peninsula, are very different in the two flanks of the Apennines chain. On the Tyrrhenian side, the drainage network has a rectangular pattern characterized mostly by main streams parallel to the NW-SE tectonic structures, combined with shorter segments that locally cross the ridges. Indeed, the extensional basins are mostly drained by this hydrographic network; few internally drained basins (Colfiorito, Castelluccio, and Fucino) are located along the regional watershed. Along the main rivers and their tributaries at least three orders of fluvial terraces are located, the older of which has been referred to middle Pleistocene (Bossio & *alii*, 1993; Bartolini, 2003; Capezzuoli & Sandrelli, 2004). We have studied the longitudinal profile of some of these streams: Cecina, Era, Elsa, Pesa, Sieve and Arno (fig. 6a). Since at the study scale all these streams are fourth or fifth Strahler order except the Arno River that is sixth order, we have extracted the long profile of the Arno River from the 250 m DEM to get an example of a stream flowing from the chain axis to the Tyrrhenian Sea (fig. 6b). The Arno River has a concave up long profile characterized by a stepwise pattern composed by several knickzones (fig. 6b) that correspond to extensional basins. The long profiles of the other streams, including the portion of the Arno upstream of

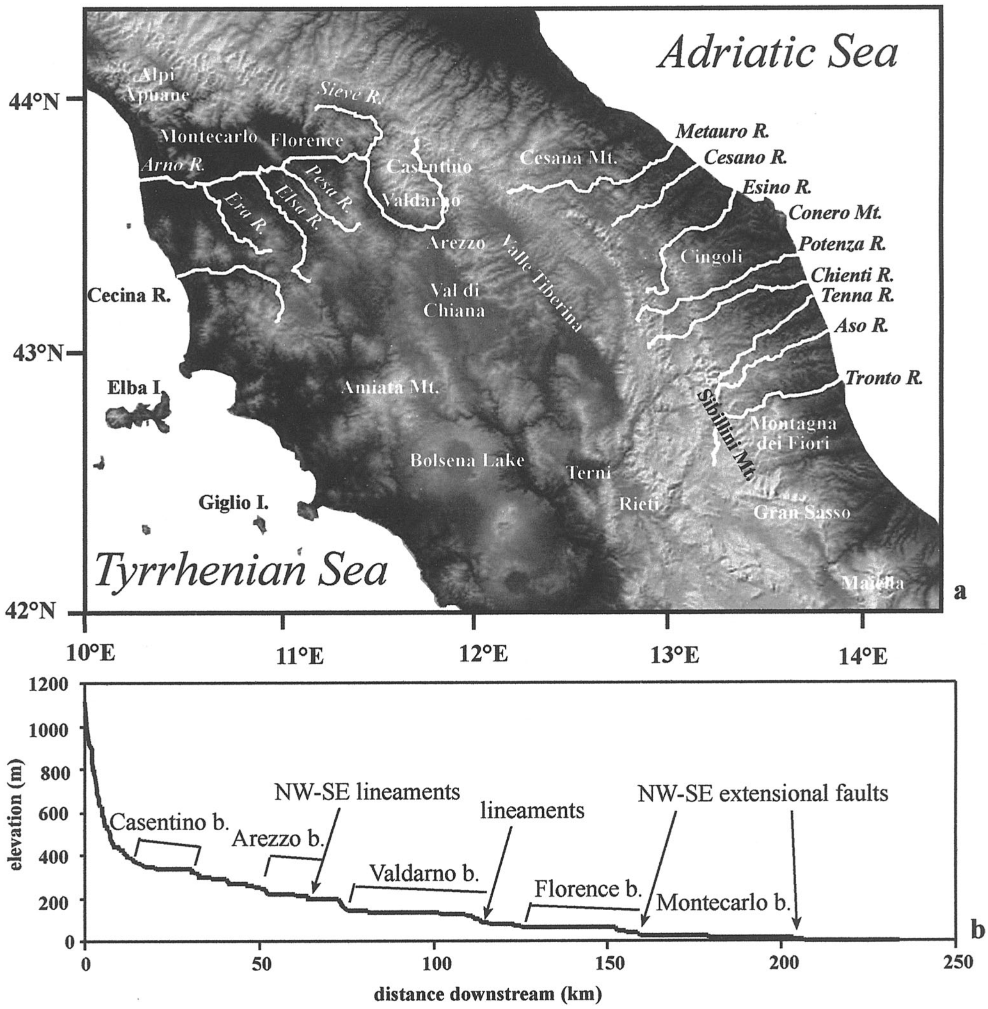


FIG. 6 - a) Location of the study streams flowing to Tyrrhenian and Adriatic seas. b) Longitudinal profiles of the Arno R. extracted from the 250 m pixel size DEM. Note the stepwise pattern where the knickzones, that correspond with the extensional basins, are delimited by tectonic structures.

the Sieve confluence, have been extracted from the 90 m DEM.

The Cecina and Era long profiles (fig. 7) have a regular concave up shape, interrupted by knickzones coinciding with NNE&SSW faults (Bigi & *alii*, 1992). The Elsa River has a peculiar long profile, composed of two parts, each one characterized by a concave up shape. They are separated by a knickpoint, downstream of which thick travertine, lacustrine, and fluvial deposits crop out (Amanti & *alii*, 2002; Capezzuoli & Sandrelli, 2004). Capezzoli & Sandrelli (2004) hypothesized that these deposits lay down in a lake generated by a tectonic lineament dam and, successively, reached and incised by the Elsa headward erosion.

The Pesa River long profile (fig. 7), characterized by a low concavity (tab. 1), shows a very straight segment at elevation lower than ~350 m. Below ~200 m of elevation, this segment coincides with NW-SE lineaments.

The long profile of the portion of the Arno River upstream of the Sieve confluence (fig. 7) is characterized by two wide knickzones that correspond to the Valdarno, Arezzo, and Casentino extensional intermontane basins.

TABLE 1 - Long profile indices

	σ	θ	raw k_s	normalized k_s*
Cecina	0.67	0.58	0.20	0.08
Era	0.56	0.55	0.10	0.05
Elsa	0.59	0.30	0.03	0.04
Pesa	0.31	-0.01	0.01	0.06
Arno (upstream of the Sieve confluence)	0.60	0.62	0.36	0.11
Sieve	0.14	0.14	0.02	0.04
Metauro	0.56	0.46	0.13	0.19
Cesano	0.41	0.44	0.08	0.12
Esino	0.64	0.47	0.11	0.15
Potenza	0.52	0.31	0.04	0.14
Chienti	0.51	0.74	1.04	0.31
Tema	0.65	0.79	0.97	0.39
Aso	0.61	0.80	0.55	0.21
Tronto	0.50	0.36	0.12	0.31

* k_s values are normalized to a reference concavity index, that is the mean value of concavity calculated separately for rivers draining the Tyrrhenian flank ($\theta = 0.36$) and the Adriatic flank ($\theta = 0.55$).

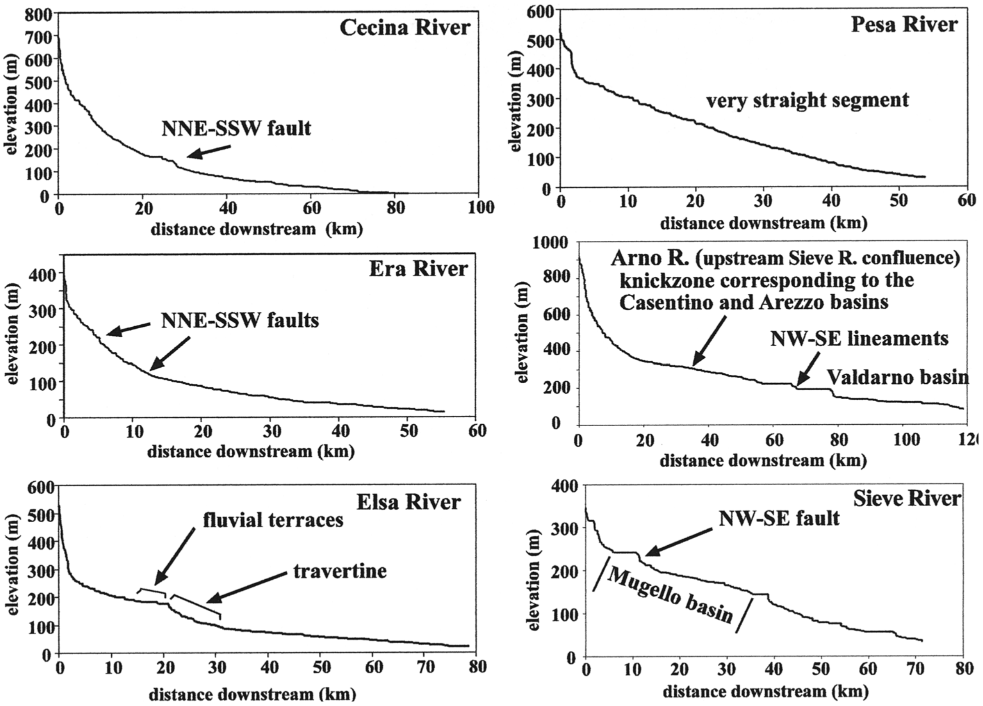


FIG. 7 - Longitudinal profiles of the streams draining the Tyrrhenian side of the Apennines. They have been extracted from the 90 m pixel size DEM.

Between the Arezzo and Valdarno basins, the knickpoints are coincident with several tectonic lineaments (Bigi & *alii*, 1992).

The Sieve River long profile has one of the less pronounced concave up shape, with a low values of concavity (tab. 1). A particularly well defined convex segment between 100 and 250 m of elevation coincides with the intermontane basin of Mugello (fig. 7).

On the Adriatic side of the Apennines, the drainage pattern is generally characterized by closely spaced, parallel streams that follow relatively straight paths toward the sea (fig. 6a). More in detail, in the mountain chain, streams are locally parallel to the NW-SE tectonic structures and form very deeply incised gorges when they cross thrusts and anticlines. In the hilly coastal belt, the drainage pattern is more regularly parallel, apparently influenced by the regional E-NE tilting that affected the Pliocene and Pleistocene deposits (Bigi & *alii*, 1995; Centamore & Nisio, 2003). Here it appears also partially influenced by the presence of topographically more elevated areas from which the streams seem to sweep away (Dramis & *alii*, 1991; Coltorti & *alii*, 1996; Di Bucci & *alii*, 2003): these areas (e.g. Mt. Cesana, Cingoli, Mt. Conero) usually correspond to the outcrop of older rock-types.

Most streams draining the Apennines to the Adriatic Sea are characterized by at least three orders of fluvial terraces and, also here, the older order has been referred to middle Pleistocene (Calderoni & *alii*, 1991; Nesci & Savelli, 1991; Coltorti & *alii*, 1996; Mayer & *alii*, 2003).

The Metauro River has a sinuous course that follows a sort of stepwise general pattern (fig. 6a). In particular, it cuts perpendicularly (with a NE-SW trend) across compressive structures and anticlines, but always in correspondence of their periclinal closures; then, it flows parallel to them (with a NW-SE trend), where mostly turbidites crop out. The Metauro River has a concave up long profile without convex segments (fig. 8).

The Cesano River, draining a sort of topographic low, flows for 60 km straight to the sea from a head at a relatively low elevation (~800 m). It has a concave up long profile, characterized by a moderate concavity (tab. 1) and by two knickpoints, that correspond to thrusts (fig. 8).

The Esino River, after flowing parallel to the Mt. S. Vicino ridge and cutting across it, follows a relatively straight NE-SW path for ~10 km, curves to the SE, and then again goes straight to the sea. Its long profile has a concave up shape with moderate values of concavity (fig. 8; tab. 1). The portion upstream of ~500 m of elevation is convex and coincides with the outcrop of carbonate and marls. Crossing the thrust that overrides these rock-types on turbidites, the profile is concave up and becomes flat just before a knickpoint. This corresponds to a deeply incised gorge and to the outcrop of Calcare Massiccio (Auct.), a massive carbonate, that is the oldest (Lias) lithology of the area.

The Potenza River, that follows a relatively straight path to the Adriatic Sea, has a concave-up long profile characterized by a huge knickpoint partially oversized by no data pixels of the DEM (fig. 8). The flat segment just upstream of the knickpoint corresponds to a widening of the valley and aggradation. Also in this case, the knickpoint correspond with the Calcare Massiccio outcrop and with a very deep and narrow valley.

The longitudinal profile of the Chienti River, that has a drainage pattern very similar to the Potenza one, is con-

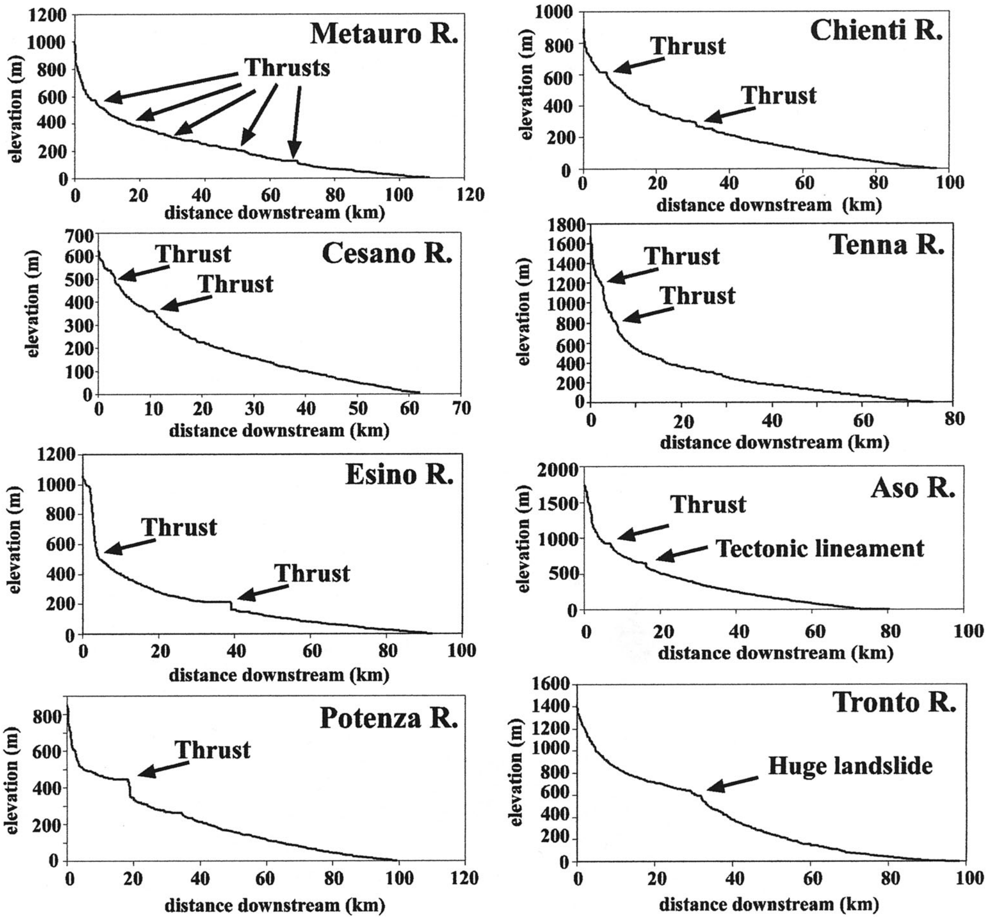


FIG. 8 - Longitudinal profiles of the streams draining the Adriatic side of the Apennines, extracted from the 90 m pixel size DEM.

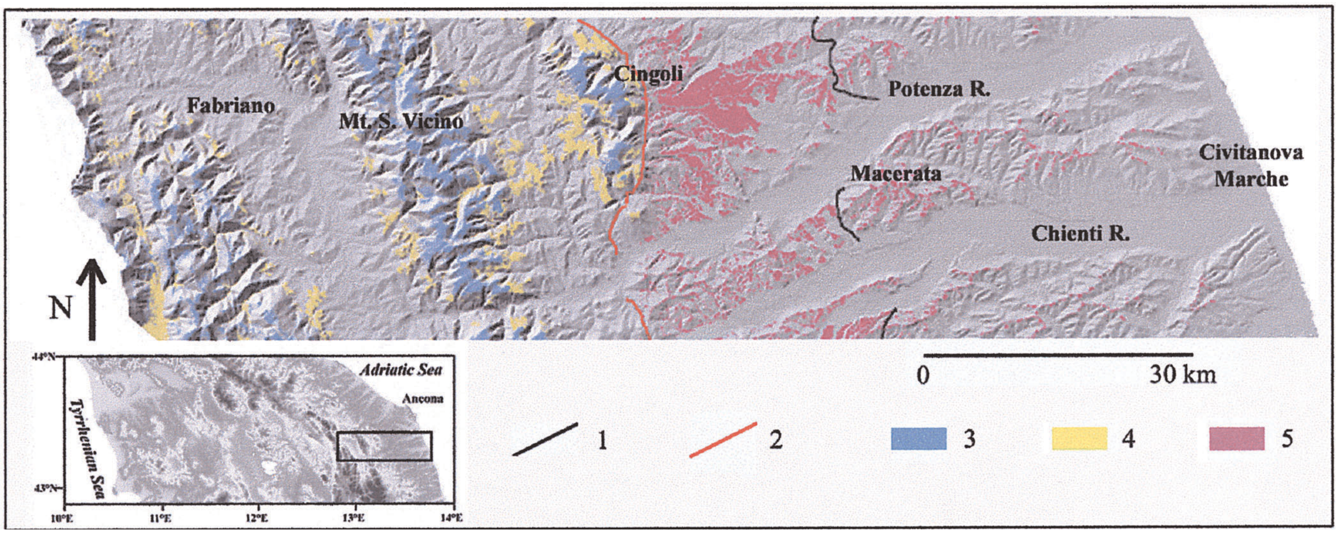


FIG. 9 - Location of the three groups of low relief surfaces in a study area south of Ancona. 1) Pliocene/Pleistocene boundary; 2) most outer outcropping compressive structures; 3) low relief surfaces (slope < 15°) standing above 650 m of elevation; 4) low relief surfaces (slope < 15°) standing between 430 and 650 m of elevation; 5) low relief surfaces (slope < 5°) standing between 195 and 430 m of elevation. The two groups located at higher elevations cut across carbonate, marl and turbidite Tertiary rock-types. The third one, east of the compressive structures, is underlain by lightly deformed Pliocene/Pleistocene marine to continental deposits.

cave up, although two small knickpoints are coincident with compressive structures (fig. 8). The one at ~600 m of elevation corresponds to a very narrow valley.

The Tenna River has one of the most concave up long profile among all the analyzed streams (fig. 8). In its most upstream portion, above 800 m of elevation, a knickzone is bounded by two thrusts (at 800 and 1200 m of elevation respectively). Similarly, the Aso River long profile is very much concave up (concavity ratio of 0.61) with a convex segment in its most upstream portion. The knickzones of both streams are coincident with the Calcare Massiccio outcrop.

The Tronto River has a peculiar drainage pattern: most of this course is oriented roughly SW-NE, while its upstream portion trends around N-S. Similarly, its long profile is divided into two concave up parts that coincide with the above mentioned drainage pattern bipartition (fig. 8). The knickpoint that separates the two parts corresponds to a landslide (Centamore, 1986), located on the downstream right.

We measured the profile concavity by both σ and θ, and the profile steepness index of all the study streams (tabs. 1, 2). In the log Area – log Slope analysis, the transi-

TABLE 2 - Mean values of the long profile indices

	σ_{mean}	θ_{mean}	Raw $k_{s\text{-}mean}$	normalized $k_{s\text{-}mean}$
Tyrrhenian flank	0.48	0.36	0.11	0.06
Adriatic flank	0.55	0.55	0.19	0.23

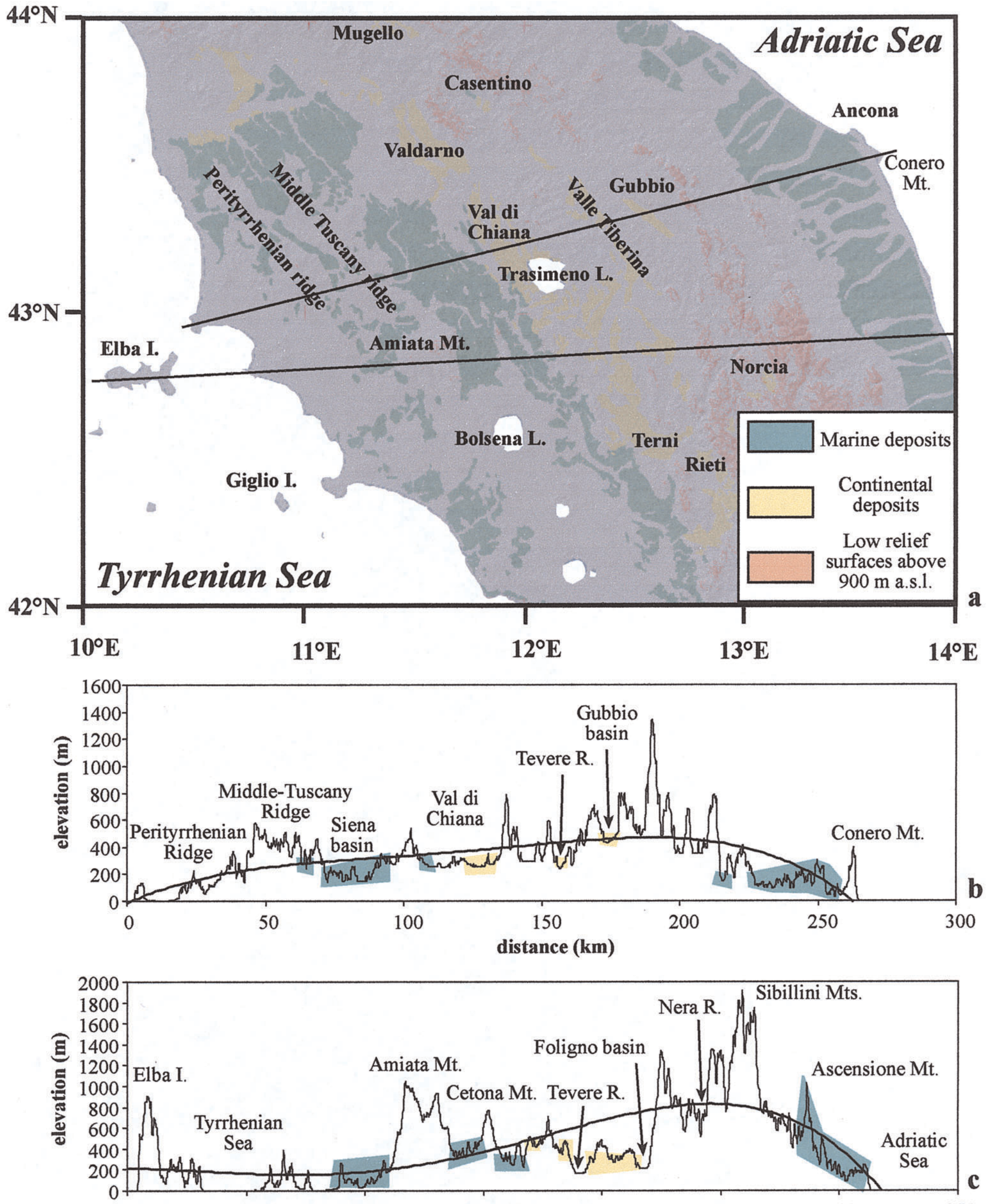


FIG. 10 - a) Map of the Pliocene-lower Pleistocene marine (green) and continental (yellow) deposits of central Italy according to the Structural Model of Italy (Bigi & *alii*, 1992) and by Carta Geologica d'Italia Interattiva, 1:100.000 (Amanti & *alii*, 2002). In the figure the location of low relief surface (pink) above an elevation of 900 m is reported. b, c) Topographic cross-sections across central Italy with the indicative location of the Pliocene-lower Pleistocene marine (green) and continental (yellow) deposits. Both map and profiles show that there was a main chain, with several lakes, ~100 km wide and presently coincident with the most uplifted portion of the Apennines. To the east, several ridges were emerged.

tion between hillslope/colluvial channels and fluvial channels can be identified by an abrupt decrease of channel slope with increasing drainage area (Duvall & *alii*, 2004). Since these features are absent in the analyzed plots, we have chosen to restrict the linear regression to regions downstream of a basin area greater than 10 km^2, not including the basin portion where debris flows could strongly influence the channel profile slope (Whipple, 2004).

According to the scheme summarized by Whipple (2004), most of the stream long profiles have a moderate concavity (tab. 1). Just two long profiles, relative to the Pesa and Sieve rivers, both draining the Tyrrhenian flank of the Apennines, have very low values of concavity reflecting the straight shape of their profiles (tab. 1; fig. 7). The Aso long profiles is the most concave-up (σ=0.61 and θ=0.80), although Tenna and Chienti profiles show very high values of θ, and Cecina and Esino of σ (tab. 1). We calculated the raw steepness index, but we also modeled it, normalizing according to reference concavity indices. The reference θs are the mean values of concavity calculated separately for the river draining the two flank of chain (tabs. 1, 2). The k_s normalizing facilitates the direct comparison among the basins and the correlation of steepness values with regional and local tectonics, and with strong lithologic contrasts (Snyder & *alii*, 2000; Whipple, 2003). The Pesa and the Sieve steepness indices are the lowest, as well as all the streams draining the Tyrrhenian side of the Apennines show lower values of both k_s and normalized k_s (tabs. 1, 2). On the Adriatic flank, the Chienti, Tenna, and Aso rivers long profiles has very high values of k_s, whereas the other stream profiles, some of which showing very well defined knickpoints in correspondence with compressive structures, have steepness indices comparable with the Tyrrhenian side ones (tab. 1). The normalized k_s anyway are definitely higher on the Adriatic flank of the chain (tabs. 1, 2).

In summary, most of the stream profiles show moderate concavity values, traditionally associated with channels experiencing uniform rock uplift, rock erodibility, and climate (Roe & *alii*, 2002; Duvall & *alii*, 2004; Whipple, 2004). Anyway, in the Tyrrhenian side of the Apennines, the stream long profiles are less concave-up and less steep, whereas in the Adriatic flank they have higher values of both concavity and steepness indices (tab. 2).

Low relief surfaces

To get more detailed information on the central Apennines landscape evolution, we have tried to find topographic evidence of the low relief surfaces that many Authors described as relicts of old landscapes. We analyzed a 20 m pixel size DEM of an area located just south of Ancona. We have chosen a portion of the Adriatic side of the chain, because it is not affected by the extensional tectonics that makes more complex the reconstruction of the landscape evolution in the Tyrrhenian side.

Analyzing the frequency histogram of elevation, we noted that it was polymodal. Thus we looked for surfaces of low local relief at different elevation ranges. We found out that there are three groups of them (fig. 9): two are in the western part of the study area and are characterized by slope < 15°. The one at higher elevation is located mostly on the crest of mountains, cutting across carbonates and marls. The second one is inset into the flanks of the range and is underlain mostly by turbidite deposits and locally by marls and carbonates.

A third surface, located more to the east (fig. 9), is much less steep (slope < 5°) and it is underlain by lightly deformed Pliocene marine deposits and by marine to continental Quaternary deposits. This surface is separated from the other two by the most eastern outcropping compressive structures (fig. 9).

PLIOCENE AND LOWER PLEISTOCENE GEOLOGIC CONSTRAINS

To add a general final picture to all the collected data, we have drawn a map of the Pliocene-lower Pleistocene marine and continental deposits of central Italy (fig. 10a), according to the Structural Model of Italy (Bigi & *alii*, 1992) and by Carta Geologica d'Italia Interattiva, 1:100.000 (Amanti & *alii*, 2002). In the figure we also show the location of low relief surface above an elevation of 900 m that, together with the continental deposits, gives an idea of the emerged portion of the chain in the Pliocene-lower Pleistocene. Indeed, fig. 10a shows a ~100 km wide belt characterized by a relatively rugged topography and by several internally drained basins occupied by lakes in the Tyrrhenian side, i.e. in the portion of the Apennines affected by extensional tectonics. In the westernmost part there was the deposition of marine sediments, in general coarser and coarser towards the chain margin (Buonasorte & *alii*, 1991), although several ridges (Perityrrhenian and Middle Tuscany ridges, Elba Island) were already emerged as islands. Therefore, in the Pliocene-lower Pleistocene, the tops of these ridges were shaped by surface processes, as confirmed by low slope surfaces found at Mt. Cetona (Coltorti & *alii*, 1999) and in the Elba Island (Centamore & *alii*, 1988). Moreover, in this island, the lack of Miocene and Pliocene deposits (Barberi & *alii*, 1967) suggests the hypothesis that it could be emerged even before.

Figg. 11b and c represent two cross-sections where the location of the Pliocene-lower Pleistocene marine and continental deposits is roughly indicated. In the figures, the 4th polynomial order trend-line that fits the topography shows the ~100 km wide belt of fig. 10a coincident with the most uplifted portion of the present Apennines. In the western flank of the chain the general trend of the topographic bulge is disrupted by the extensional tectonics that originated the basins. On the Adriatic flank of the chain, the trend is much regular, although local features as the topographic high of Mt. Conero could partially disturb it.

DISCUSSION

The morphometry analysis coupled with the Pliocene-lower Pleistocene geologic constrains indicates that the

Apennines topography comes from the superimposition of two main wavelengths (fig. 4). The short wavelength is related to local effects of regional tectonics. Indeed, in the Tyrrhenian side, the wavelength spacing is generated by the extensional tectonics that originated basins younger and younger going eastward. The spacing, and so the extensional tectonics, influenced the local stream orientation, inducing the formation of the rectangular drainage pattern (fig. 6), and the channel slope, generating knickpoints and knickzones (fig. 7). Indeed in many long profiles of rivers draining the Tyrrhenian flank of the Apennines, wide knickzones and straight segments correspond to extensional basins (fig. 7). They make the profile shape less concave up (fig. 7; tab. 1), suggesting the streams are still adjusting a tectonic perturbation of their courses. This perturbation, related to the extension, influenced also the values of the profile steepness. Indeed, although all the Italian Peninsula experienced a regional uplift that should have steepened stream profiles, on the Tyrrhenian side of the chain the extensional tectonics partially mitigate the uplift influence, lowering the steepness indices.

On the Adriatic flank the short wavelength spacing is related to compressive structures that thrusted marls and carbonates on turbidite successions. Although the stream incision generated narrow valleys or very deep gorges when crossing the carbonates and marls, the different erodibility of these rock-types induced the formation of knickpoints in the stream long profiles (fig. 8). Anyway, this well defined knickpoints related to lithologic variations seem not to influence too much the profile steepness indices (tab. 1), suggesting the main factor that makes the Adriatic streams steeper is the regional Quaternary uplift. Therefore the wavelength spacing, linked to the selective erosion of different rocks, produced local changes of channel slope and orientation.

The second wavelength includes the whole Apennines chain reporting on a topographic bulge 200-300 km wide (figg. 4, 5), that is a record of the regional uplift started at the end of lower Pleistocene. Recently, D'Agostino & *alii* (2001) obtained very similar results more to the south and, on the basis of the strong coherence between the long wavelengths of topography and of the free air gravity anomalies, hypothesized that the broad Quaternary arching of the Apennines is dynamically supported by mantle convection. Before this arching, in the Pliocene-lower Pleistocene, the emerged portion of the chain was a much narrower belt (~100 km wide) together with several islands to the west (fig. 10a). In the emerged portion of the Apennines, one or even more low relief landscapes (slopes < 15°) developed by the interaction between surface processes and conditions of base level slow lowering. Their remnants are presently located on mountain slopes and tops (fig. 9) and delimited by steep escarpments.

The emersion and shaping of the ~100 km wide belt and of the Tuscany ridges is confirmed by marine and continental deposits. Lower Pliocene fluvial sediments contain pebbles coming from Elba Island area (Bossio & *alii*, 1993; Amanti & *alii*, 2003). The middle-upper Pliocene marine deposits are much coarser close to both flanks of the chain (Centamore & *alii*, 2003 and reference herein), suggesting the surface processes mobilized coarse material from the inland to both Adriatic and Tyrrhenian seas.

Although the emersion of the chain was already occurring since lower Pliocene or even since Miocene, the strong long wavelength uplift started at the end of lower Pleistocene. In the Tyrrhenian side, the depositional environment progressively changed from marine to continental reporting on the emersion of the extensional basins (fig. 10) (Centamore & *alii*, 2003 and reference herein). In the Adriatic flank, alluvial deposits lay down on an erosion surface recording the marine regression (Bigi & *alii*, 1995). The broad arching affected mainly the already emerged belt (maximum rate of at least ~1 mm) (fig. 10). Indeed, moving away from the axial portion of the Apennines, on both flanks of the chain the present maximum elevation (480-500 m) of the lower Pleistocene shorelines and relative deposits (Girotti & Piccardi, 1994; Bigi & *alii*, 1995) suggests an uplift rate of around 0.5-0.7 mm/yr in the last 1 My. In the Tyrrhenian side, in the Latium and Tuscany area, the Pliocene-lower Pleistocene marine deposits crop out at elevations progressively higher to the NE (Barberi & *alii*, 1994). In the Elba Island and in the Tuscany coastal area, marine terraced deposits located at around 100-120 m and referred to middle Pleistocene, testify the involvement of these peripheral areas in the general Quaternary arching of the Apennines even if at a much less rate (~0.2-0.1 mm/yr) (Centamore & *alii*, 1988; Censini & *alii*, 1991; Bossio & *alii*, 1993; Mazzanti, 1995).

The long wavelength component of topography is also shown by the polynomial trend-line that best fits the relief (fig. 5). It is mostly at an elevation of 200 m, suggesting the major drainage patterns to both Adriatic and Tyrrhenian seas are defined by the long-wavelength arching of the Apennines. Indeed, even though in the southernmost swath profile the topography reaches higher elevations (figg. 4 and 6), the relief is more or less the same (~750 m) in both profiles in correspondence with the line of the highest peaks. The strong influence of the Quaternary Apennines uplift on drainage development is also shown by the stream profile steepness indices. In fact, they indicate, independently by rock-types changes, the rivers courses steepen as a consequence of a regional vertical tectonism, whose action is mitigated by the extension on the Tyrrhenian side.

CONCLUSIONS

Performing a morphometry analysis we have studied the tectonic geomorphology of the north-central portion of the Apennines (Italy): we have explored the relationships between the Apennines topographic features and both local and regional tectonics. Coupling this analysis with the geologic constrains of the Plio-Pleistocene deposits map (fig. 10), we tried to figure out the topographic evidence for how Apennines landscape was shaped by its emergence above sea level, providing with information on the long-term landscape evolution. Casting the results into the general picture of the Apennines evolution drawn by previous studies and taking account of the geologic constrains proposed in fig. 10, we could hypothesize the following.

1) During the slow emergence of the chain in the late Tertiary, surface processes shaped low relief landscapes in slow lowering base level conditions. Nowadays, relicts of them are preserved on mountain tops and slopes. In detail, the low relief surfaces extracted in the Marche region, but present all along the Italian Peninsula, suggest that the slow emergence of the chain allowed the development of one or even more landscapes.
2) Although the hydrographic network developed differently in the two sides of the chain (in the Adriatic flank, the main rivers progressively incised perpendicular to the compressive structures, whereas in the Tyrrhenian side, the influence of the active extension induced the formation of a rectangular network and locally internally-drained basins), the major drainage patterns to both seas are defined by the long wavelength arching of the Apennines. Indeed, the long profiles concavity and steepness index values suggest the study streams are still adjusting the broad uplift perturbation, although its action is partially mitigated by the extensional tectonics.

In conclusion, the Apennines landscape results as strongly influenced by a) the regional vertical tectonism that allowed the development of low relief landscapes before middle Pleistocene, but successively rapidly uplifted them, inducing river systems disequilibrium, a strong fluvial erosion, and the formation of most of the present Apennines topography; b) the local deformation that directly (the extension in the Tyrrhenian side) and indirectly (the selective erosion of the thrusted rock-types in the Adriatic side) produced a troughs and ranges pattern (short wavelength), and variation of stream slope and orientation. Therefore, the Quaternary strong uplift results as the main shaping factor of the present Apennines landscape.

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