The Plio-Quaternary uplift of the Apennine Chain: new data from the analysis of topography and river valleys in Central Italy

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Abstract
This study aimed at the reconstruction of magnitude and timing of uplift of a wide sector of the Central Apennines (Italy) by means of morphometric and morphostructural analyses. In the internal portion of the chain (where stratigraphic and geomorphological markers of past sea-level positions are lacking) the study was based on analysis of erosional landforms and river valleys.
A large-scale topographic analysis was performed, processing 90-m and 230-m DEMs. The spatial distribution of several morphometric parameters, together with characteristic wavelengths of relief, allowed the distinction of three main regions affected by different cumulative surface uplift and tectonic/erosional fragmentation: a Peri-Tyrrhenian Belt; an Axial Belt; a Peri-Adriatic Belt.
Particular attention was devoted to fluvial landforms, with analysis of longitudinal profiles and geometric pattern of the main stream-trunks and their relations with major structures. Major differences occur between the Tyrrhenian and Adriatic valley systems, the former being generally longitudinal and showing overall concave-upward longitudinal profiles, whereas the latter are generally transverse and possess less regular longitudinal profiles. Topographic features and river valleys architecture seem related to different styles and amounts of uplift in the three Belts.
Within the study area, a narrower coast to coast transect (Gaeta-Vasto Transect, GVT) was investigated in detail, devoting particular attention to its axial sector, lying around the Apennines main divide (main divide area: MDA), and a possible scheme of the Quaternary surface uplift inside

this transect was proposed. In the MDA, the main stages of landscape evolution and river network organization were reconstructed by analysis of paleosurfaces coupled with analysis of relic and present-day hydrographic network. This allowed recognition of a major phase of surface uplift (exceeding 1500 m in the Meta-Mainarde massif) occurred in response to thrusting during the Pliocene, whereas for the Quaternary uplift a minimum value around 400 m was estimated.
Our study suggests that, during the Quaternary and in the GVT, the Peri-Tyrrhenian Belt suffered a subdued uplift operating over small wavelengths (10-15 km), while Axial and Peri-Adriatic Belts were subject to a stronger and long-wavelength (90 km) surface uplift, with maximum values (about 700 m) shifted NE of the Axial Belt and tapering to zero towards the Adriatic coast. The reconstructed pattern of uplift is coherent with the topographic properties of the three Belts and with the observed drainage features.
Keywords: *Morphometric analysis; DEM; Paleosurface; Drainage network; Surface uplift; Central Apennines.*

1 Introduction
In the last decades, many attempts to estimate timing and magnitude of topographic growth affecting the Apennines chain were performed, often resulting in markedly contrasting results (see, among the others: Demangeot, 1965; Westaway, 1993; Bordoni and Valensise, 1998; Ascione and Cinque, 1999; Calamita *et al.*, 1999; Carminati *et al.*, 1999; Amato, 2000; Bartolini, 2003; Pizzi, 2003). These disparities mainly result from the quite complex tectonic evolution of the chain and the lack of clear markers depicting vertical displacements of topographic surface, particularly in the

axial portion of the thrust-belt. In this paper, we aim at the assessment of cumulative surface uplift affecting a narrow transect of the Central Apennines, during the Quaternary. Central Apennines are believed to have been uplifted mainly during Quaternary times, particularly in their axial portion (D'Agostino *et al.*, 2001; Pizzi, 2003).

Surface uplift is the displacement of topographic surface with respect to the geoid (England and Molnar, 1990). Estimations of past surface uplift are normally obtained from the present elevation of geomorphic and stratigraphic markers created at well known absolute elevations, such as marine terraces and deposits. These are generally absent in orogens interiors, where erosional landscapes dominate. This is also the case of Central Apennines, where recent markers of marine origin are present only on the marginal sectors of the uplifted belt. Therefore, it becomes crucial to exploit also other, less direct indicators of past base levels, such as fluvial terraces, planation surfaces and similar landforms, although they usually give less precise constraints. Also very useful is to consider all the geomorphological evidence that reveals and quantifies the relative displacements occurred within the uplifted regions, particularly between all the ones carrying paleo-sea level markers and others that lack similar features. The use of such a wider approach implies a more complete geomorphological analysis of the study area, aimed at unraveling the long-term evolution of its landscape, with special attention to fault scarps, erosional and depositional terraces, upliftdriven dissection phases, river longitudinal profiles etc.

In a wide-spectrum morphotectonic study of orogenic areas, extensive topographic analysis through numerical processing of DEMs (Mayer, 2000 and references therein) is a powerful tool to decipher first-order statistical and morphometric properties of orogens landscape. These properties rely on the spatial wavelength over which both endogenic and external factors operate, and the competition between rock uplift and erosional degradation (Schmidt and Montgomery, 1995; Burbank *et al.*, 1996; Willett, 1999; Kühni and Pfiffner, 2001; Montgomery and Brandon, 2002), so a link between macro-scale processes and topography can be established (Hovius, 2000).

Fluvial processes play a major role in shaping orogenic landscapes (Howard *et al.*, 1994; Koons, 1995; Hovius, 2000), often inducing complex feedbacks with tectonic and geodynamic processes (Kooi and Beaumont, 1996). River network response to both local and large-scale tectonics and uplift is quite complex and may result in a wide series of phenomena, the most important being: changes of drainage pattern (Holbrook and Schumm, 1999); modification of longitudinal profiles

(Whipple and Tucker, 1999; Tebbens *et al.*, 2000; Riquelme *et al.*, 2003; Starkel, 2003); genesis of terraces, captures, deviations, water gaps, wind gaps and others (Merrits *et al.*, 1994; Jackson *et al.*, 1996; Bonnet *et al.*, 1998; Alvarez, 1999; Keller *et al.*, 1999; Tyracek, 2001; Montgomery and Lopez-Blanco, 2003; Clark *et al.*, 2004; Jamieson *et al.*, 2004). Therefore, river network examination combined with morphometric analysis of topography, becomes a useful tool to gain insights into the long-term geomorphological evolution of an active mountain belt, being able to give some constraints to timing and magnitude of surface uplift affecting the chain.

2 Area descriptions and methods

2.1 Study area

The Apennines chain, located between the Tyrrhenian and the Adriatic seas, is a segment of the Circum-Mediterranean mountain system. The central portion of the Apennines chain (Fig. 1) results from shortening occurred between Miocene and Lower Pleistocene. Thrusting with a general NE sense of transport involved sedimentary thrust-sheets related to carbonate platform-to-slope domains and their interposed basins (Parotto and Praturlon, 1975; Patacca *et al.*, 1990). Timing and forward propagation of compressive front are mirrored by eastward younging of Early Miocene to Lower Pleistocene foredeep siliciclastic deposits (Patacca *et al.*, 1992; Cipollari and Cosentino, 1995), which represent the highest stratigraphic levels of the main thrust-sheets.

Since the Late Miocene, extensional tectonics affected the internal portion of the chain (Malinverno and Ryan, 1986; Sartori, 1990; Patacca *et al.*, 1990; Cavinato and De Celles, 1999). The resulting Tyrrhenian Sea back-arc basin extended progressively to the E, causing the drowning of the internal sector of the wedge and the formation, since Lower Pliocene, of coastal grabens (peri-Tyrrhenian basins) and interposed horsts along the whole SW flank of the chain. Subsidence affecting the peri-Tyrrhenian grabens of the Central Apennines ranged between 1000 m and well over 2000 m since the Pliocene (Brancaccio *et al.*, 1991; Cipollari *et al.*, 1999). This tendency strongly slowed down and was locally replaced by slight uplift (few meters) during Middle-Late

Pleistocene (Barbieri *et al.*, 1999; Bordoni and Valensise, 1998), when a widespread volcanism affected the Tyrrhenian flank of the chain (Cavinato *et al.*, 1994). Internal sectors definitively emerged since the Late Miocene, during shortening of the chain, and the main ridges were subject to a total surface uplift locally exceeding 1500 m during the whole Late Miocene–Quaternary time interval. Along the Tyrrhenian margin, in the Gaeta horst block, the highest marine abrasion terrace is at 230 m a.s.l. and is tentatively ascribed to the Early Pleistocene.

In the axial zone of the chain, emersion took place between Late Miocene and Lower Pliocene, the youngest marine deposits being probably Lower Pliocene in age (foredeep sandstones and scattered thrust-top basin deposits). Plio-Quaternary extensional tectonics was responsible for the generation of some important intramontane depressions (Doglioni *et al.*, 1998; Galadini, 1999; Miccadei *et al.*, 2002; Bosi, 2004). Maximum elevation of the main ridges often exceeds 2200m, up to 2800 m. Some authors hypothesize that major topographic growth (up to 1500 m) in this sector of the chain took place almost exclusively since Middle Pleistocene times (D’Agostino *et al*., 2001; Pizzi, 2003). Both Pleistocene uplift and extensional tectonics are believed to have driven an impressive morphogenesis in this portion of the chain, producing deep changes in elevation and morphology (D’Agostino *et al.*, 2001), and shaping primitive tectonic landforms, passive structural landforms and erosional landforms (D’Alessandro *et al.* 2003 and references therein).

The external sector of the chain, with maximum elevation lower than 1500 m and regularly decreasing towards the Adriatic Sea, was subject to a broad uplift since Middle Pleistocene, resulting in a general NE-tilting of the Late Pliocene - Lower Pleistocene marine deposits (Cinque *et al.*, 1993; Pizzi, 2003). This uplift is well constrained by age and distribution of marine deposits, reaching a maximum elevation of about 700 m above sea level at the outer front of the belt and tapering to zero towards the coast.

Some general models of the Tyrrhenian-Apennines system (Doglioni, 1991; Cavinato and De Celles, 1999) suggest that topographic growth of the Apennines thrust-belt is related to an orogenic

wave rapidly migrating (rates of the order of 1-3 cm/yr) towards the E-NE, simultaneously with the opening of the Tyrrhenian back-arc basin and the forward propagation of frontal wedge accretion.

2.2 Methods

Our large-scale morphometric analysis of the study area was performed using a 230-m grid DEM for a first order description of the relief properties. We calculated several morphometric parameters (such as: average elevation, dispersion, skewness, elevation/relief ratio and others; see, for a review: Klinkenberg, 1992 and references therein) and estimated the characteristic wavelength of relief for the main physiographic compartments in the chain.

Average elevation holds direct information about the cumulative surface uplift of a given area (England and Molnar, 1990); standard deviation (hereinafter, *dispersion*) is a measure of roughness of topography; skewness depicts the asymmetry of a frequency distribution, with left-skewed distributions (i.e.: positive skewness values) pertaining to landscapes with landmass concentrated at low elevations and right-skewed distributions (i.e.: negative skewness values) pertaining to landscapes with landmass sited above its average elevation; elevation/relief ratio (E/R) gives a firstorder picture of the degree of fragmentation of topography, due to both erosional or tectonic processes.

Thematic maps showing the spatial distribution of these parameters (Fig. 2) were produced using circular moving windows with 5 km radius, following the procedures described, among others, in Guzzetti and Reichenbach (1994) (see also: Deffontaines *et al.*, 1994; Weissel *et al.*, 1994). High values of average elevation and E/R, coupled with relatively low dispersion and close to zero or negative skewness, associate with areas experiencing large scale uplift and negligible tectonic/erosional fragmentation. On the contrary, high dispersion, low E/R and positive skewness characterize more tectonically fragmented and/or dissected areas.

We intend characteristic wavelength of relief as the linear dimension of a sampling window which encompasses the maximum relief range in a given area. Depending on the window size,

characteristic wavelength is related to the average width of valleys and/or tectonic depressions (5-20 km wavelengths; this is also said topographic *grain*), up to the half-width of the orogen (50 km to >> 100 km wavelengths) (Ahnert, 1984; Guzzetti and Reichenbach, 1994; Koons, 1995). The relief range in the study area was sampled using moving circular windows with radii increasing from 5 km to 25 km (which correspond to sampling wavelengths between about 10 km and > 40 km), and averaging the corresponding relief values along 180 angular directions; we then selected areas with homogeneous characteristic wavelength for each sampling radius. This resulted in a firstorder subdivision of the study area in three main physiographic belts (section 3.1).

The drainage net was also analyzed in order to discriminate older from younger valleys and, more in general, to reconstruct age relationships between river paths and tectonic structures. Longitudinal profiles of major rivers (two from the Tyrrhenian slope and three from the Adriatic flank) were extracted from 90-m DEM (obtained by SRTM elevation data) and analyzed in order to outline and locate areas of recent uplift.

We then focused on the reconstruction of the long-term geomorphological evolution of a narrower area, extending on a transect from Gaeta to Vasto (Gaeta-Vasto Transect, hereinafter GVT; Fig. 1). We based onto reviewed literature and original data regarding distribution of Pliocene-Quaternary shallow marine deposits and terraces, erosional surfaces (hereinafter named, according to the Italian tradition, *Paleosurfaces*), amount of dissection and vertical offsets in different areas and moments of the Plio-Quaternary history.

A detailed morphostructural study was carried in a crucial and poorly known area located in the central portion of the GVT (Fig. 1) and including the Apennines main divide (here opposing the Sangro and Volturno rivers basin heads). Here our major attention was devoted to erosional and depositional landforms related to ancient local base-levels, wind gaps, hanging and/or beheaded valleys as well as tectonic landforms such as anomalies in long-river profiles, fault scarps and faultline scarps.

3 Analyses and results

3.1 Large-scale morphometric analysis of the study area

Based on both visual and morphometric analysis of the landscape, the study area can be subdivided into three different zones that we label as *Belts* in consideration of their regional extent parallel to the strike of the chain. From the SW to the NE these three zones are: the Peri-Tyrrhenian Belt, the Axial Belt and the Peri-Adriatic Belt (Fig. 2a). The first zone is characterized by a rugged topography, with blocky, fragmented ridges (peaks up to 1500 m) and large, flat floored valleys lying at low elevations (Volturno Plain; Latina Valley; coastal sector nearby Gaeta; from 0 to 200 m). The Axial Belt possesses wide and elongated ridges with many peaks above 2000 m, separated by narrow, V-shaped valleys whose floors generally lie at elevations from 700 m to 1600 m. The 2700 m high Majella thrust ridge is sited in a quite eccentric position with respect to the chain axis, with steep flanks above the hilly surroundings (Fig. 2a). In the Peri-Adriatic Belt the landscape is dominated by low hills whose envelope shows a gently NE-dip (about 2 %). This regular landscape partly follows the regressive top surface of the foredeep infill (Lower Pleistocene in age) and partly derives from the coeval smoothing of the most external imbricates made of soft rocks.

This threefold partition of the area emerges also from morphometry, as the thematic maps in Fig. 2b-c-d and Tab.1 show.

Due to its blocky relief, the Peri-Tyrrhenian Belt features the smallest characteristic wavelength of relief (about 15 km; maximum averaged relief range: 400 m; Fig. 2e). Highly positive skewness (Tab. 1) and low E/R depict the large extent of depressed areas with respect to isolated highs.

The Axial Belt shows the highest values of average elevation and E/R. Moreover, it has a greater characteristic wavelength (about 45 km; maximum averaged relief range: 670 m, Fig. 2f), even if a smaller characteristic wavelength at 20 km can be recognized (Fig. 2f). It is also characterized by a strong landmass concentration (Fig. 2b-c-d, Tab. 1), with particularly high values of average elevation and E/R (> 1400 m and > 0.600 respectively), and a relatively low value of dispersion

(about 200 m) in the so called Marsica Province (the region encompassing Meta-Mainarde, Montagna Grande and Mt. Greco massifs, Fig. 1).

The Peri-Adriatic Belt has the greatest characteristic wavelength (> 45 km; maximum averaged relief range: 340 m; Fig. 2g) together with low average elevation and dispersion (Fig 2b-c-d, Tab. 1). Close to zero skewness and a relatively high E/R (Tab. 1) depict a plateau-like, slightly dissected landscape.

Morphometric properties of the Peri-Tyrrhenian belt suggest that it underwent strong tectonic fragmentation, with uplift operating over small wavelengths (10-15 km), comparable with average fault spacing and fault-block dimensions in this portion of the chain. Low average elevation of the main depressions (close to sea level), relatable to long-term subsidence of the coastal grabens and locally compensated by sedimentation, dominates the hypsometric features of this belt.

In the Axial Belt, average elevation and E/R suggest a stronger cumulative surface uplift than in the two other belts. The characteristic wavelength of relief (45 km) suggests the role of uplift operating over large areas (linear dimensions > 40 km), and going beyond the control exerted by the average spacing (< 20 km) of the main thrust-anticlines and high-angle faults. The quite low dispersion in the Marsica province denotes a poor degree of tectonic fragmentation of this portion of the Axial Belt (Fig. 2c).

In the Peri-Adriatic Belt, morphometric properties depict a dissected, tilted plateau. This corresponds partly on the regressive top surface of the former foredeep infill (Late Pliocene to Early Pleistocene in age) and partly on a quasi-planation surface cut across Pliocene – Lower Pleistocene contractional structures. The great characteristic wavelength of relief (> 45 km) is relatable to the regional dip of this portion of the chain, consequence of a large-scale uplift, and the relatively small amount of valleys deepening.

3.2 Drainage network and fluvial valleys analysis.

In Fig. 3 the simplified hydrographic network of the study area is reported, with its main longitudinal valleys, transversal valleys, major water gaps, elbows and endorheic areas. Note that

the Apennines divide splits around some major extensional tectonic depressions (Fucino Plain and

Matese Lake), but large endorheic areas are also preserved in the Adriatic flank of the chain (Roccaraso Plains) . Moreover the Apennines divide, N of the Volturno drainage basin, does not coincide with major peaks (some high mountains of the Marsica province and Majella massif are well inside the Adriatic flank).

Within the study area, as in many other sectors of the Apennines, the Tyrrhenian and the Adriatic flanks of the chain differ also in terms of river network architectures. The Tyrrhenian rivers typically flow into longitudinal valleys, some of them hosting terraced Pliocene-Pleistocene fluviallacustrine sequences (up to 150 m thick) at their bottom. Both the two major Tyrrhenian rivers of the study area (Fig. 4a-b; Tab. 2) have longitudinal profiles with low average slope, concave-up and smooth shape. A knick is observed at 290-270 m in the Liri River, where it crosses the northern boundary of Latina Valley, in the Mt. Cairo fault zone.

The widespread occurrence of longitudinal valleys largely depends on the circumstance that the internal part of the Central Apennines (from the Tyrrhenian coast to part of the Axial Belt) is affected by important extensional tectonics since Lower Pliocene times (and progressively younger to the E) with formation of long, NW-SE trending depressions that entrapped most of the drainage lines. The fairly good grading of rivers longitudinal profiles depends on a long lasted geomorphic evolution. In fact, this portion of the chain was accreted during Middle to Late Miocene and definitively emerged in the Late Miocene. The attainment of mature longitudinal profiles was also facilitated by the fact that the main valleys follow litho-structural corridors, that is to say strips of soft rocks (synorogenic terrigenous units) intervening between hard limestone ridges. Such corridors were created by Late Miocene to Lower Pliocene phases of compressive imbrication and/or by younger (Late Pliocene – Pleistocene) extensional displacements.

On the contrary, the Adriatic rivers are typically transversal in their mid-lower course, even though longitudinal reaches of noticeable length also occur in the upper portion of the Aterno and Sangro rivers: in the case of Aterno River, they follow some important Pleistocene grabens (e.g.

Sulmona Plain, Fig. 1), while in the case of Sangro River they follow ancient fault-bounded depressions relatable to compressive structures. Lower order longitudinal streams also occur in the mid portions of the same two river basins. Compared with the rivers flowing towards the Tyrrhenian Sea, those directed to the Adriatic coast (Fig. 4c-d-e) have longitudinal profiles that are much less regular, steeper and characterized by higher values of their profile normalized integrals (Tab. 2). The Sangro River profile shows a 20 km long steep reach between 750 m and 250 m and has the highest E/R values. The Trigno and Biferno river profiles are both very steep in their upper reaches and become slightly convex where crossing the most external and youngest imbricates of the chain.

The observed transversal valleys, as the many others cutting the eastern slope of the whole Apennines chain, reflect the primary control of regional slope (overall frontal topography of the accretionary wedge), as well as the ability of major rivers to dissect the rising thrust-anticlines (see also: Mazzanti and Trevisan, 1978; Alvarez, 1999; Hovius, 2000). This scenario accounts well also for the widespread water gaps. On the other hand, both the greater average gradient of rivers longitudinal profiles and the presence of convex-up reaches lead to assume that the Adriatic flank of the chain experienced younger and/or faster uplift than the Tyrrhenian side.

3.3 Detailed morphostructural analysis of the main divide area (MDA)

Within the representative Gaeta-Vasto Transect, a more detailed morphostructural analysis was performed for the crucial and poorly known area, about 400 km^2 wide, where the Sangro and the Volturno river basin heads oppose each other along the Apennines main divide (Main Divide Area, hereinafter MDA; Fig. 5a). This area belongs to a sector of the Apennines that was subject to contractional deformation in the Lower Pliocene (Patacca *et al.*, 1992; Scrocca and Tozzi, 1999), while other tectonic phases (mainly strike-slip faulting with block-rotations) presumably took places around Late Pliocene – Lower Pleistocene (Corrado *et al.*, 1997). It is characterized by a complex structural framework, where carbonatic thrust sheets of Meta-Mainarde and Montenero Val Cocchiara units (relatable to Meso-Cenozoic slope-to-basin domains) tectonically overlay Late

Miocene - Lower Pliocene foredeep siliciclastic deposits. Deeper carbonatic thrust sheets of Mt. La Rocca, Mt. Castelnuovo and Mt. della Rocchetta units (relatable to Meso-Cenozoic shelf-to-slope domains) crop out in the eastern part of the study area (Miccadei, 1993; Di Bucci and Scrocca, 1997). Thick relics of sinorogenic siliciclastic deposits occur in all the main valleys, trapped in compressional structures, but thinner remnants can be found also in prominent morphological position, on the Apennines main divide, up to 1400 m a.s.l.

The topography of the MDA is quite rugged, with ridges up to 2100-2200 m high (Meta-Mainarde massif) to the W, and low mountains with subdued relief to the E, where the average elevation is 800-900 m a.s.l. (Fig. 5b). In the highest zone several sets of Middle-Late Pleistocene glacial cirques and troughs with related morenic deposits are preserved (Cinque *et al.*, 1990; Jaurand, 1998; Giraudi, 2003; Villani, 2005). N of the main divide, the Sangro River flows with gentle gradient between about 1000 m and 800 m a.s.l., while, S of the divide, the head streams of the Volturno River flow at lower altitude (between 900 m and 400 m a.s.l.) with slightly steeper gradients. The Apennines main divide has an average elevation of 1200 m, but it rises up to 2200 m a.s.l. when passing on the Meta-Mainarde massif.

The morphostructural setting of the MDA (Fig. 5a and 6) includes many features: the Meta-Mainarde exhumed anticlines and some eroded thrust relief belonging to the Montenero Val Cocchiara klippe, all of them bordered by thrust-fault scarps and fault-line scarps up to 1000 m high (case of the eastern escarpment of the Meta-Mainarde massif); faulted homoclines with dip-slopes to NE and fault-related scarps to SW (Mt. La Rocca, Mt. Castelnuovo, Mt. della Rocchetta and others). The term thrust-fault scarp is here used for slopes underlain by a thrust plane or a reverse fault, while the term fault-related scarp (the english rendition of “Scarpata su faglia” *sensu* Ascione and Cinque, 19979) is used to indicate a structural slope that originated along a fault due to both tectonic offset and differential erosion.

Within the MDA, the carbonatic morphostructural highs are separated each other by erosional valleys following corridors of erodible siliciclastic deposits occurring between the carbonatic

embricates (e.g.: Valle di Mezzo, Vigna Lunga Valley, Figs. 5a and 6). The faults delimiting the aforementioned homoclinal ridges are probably coeval to thrusting of the Meta-Mainarde unit and their present geomorphological evidence appears due to erosional exhumation (i.e. formation of fault-line scarps). During exhumation some spectacular water gaps were also superimposed on those ridges. However, a moderate reactivation during Lower and early Middle Pleistocene times can be suspected for the faults delimiting the Mt. La Rocca, Mt. Castelnuovo and Mt. della Rocchetta ridges to the W and SW. Evidences of Late Pleistocene to Holocene tectonic activity, resulting in few-meters displacements of glacial and slope deposits, are found N of the MDA (Giraudi, 1995; Miccadei and Parotto, 1998).

The morphostructural analysis pointed out the presence of several remnants of paleosurfaces (Fig. 6), allowing to reconstruct ancient landscapes of low local relief that include smooth hills**,** planated areas and low-gradient, sinuous valleys that nowadays appear hanging and/or beheaded. This suggests that those relic landscapes were shaped with a strong contribution of fluvial and fluvial-karstic phenomena occurred in proximity of ancient local base-levels. In our opinion, the great role played (in the past) by karstic planation finds an explanation not only in the wetter Late

Tertiary climates, but also in the circumstance that (before the Quaternary uplift and denudation events) the outcrops of impervious siliciclastic units were much wider than today and, consequently, much more superficial water was conveyed from them to the limestone outcrops (see a discussion in: Amato and Cinque, 1999).

The remnants of paleosurfaces are found above 750 m a.s.l. and reach higher than 2000 m in the Meta-Mainarde massif. A cluster of wide remnants at 1000-1200 m a.s.l. covers a large portion around the Apennines main divide (Fig. 6).

Based on their position and mutual geomorphological relationships, we distinguished the paleosurfaces remnants in four groups located at 1600-2100 m, 1200-1400 m, 900-1200 m, and 750-850 m a.s.l.. They are respectively assigned to the Lower-Middle Pliocene, Late Pliocene, Lower Pleistocene and Middle Pleistocene based on their relations with some dated formations of

the study area. Namely the Middle-Late Pleistocene fluvial and glacial deposits of the high Sangro and Volturno valleys and the Middle Pleistocene lacustrine deposits and travertines occurring near Castel S. Vincenzo (Villani, 2005).

Each paleosurfaces group is probably the remnant of an ancient low-relief landscape, shaped during a period of substantial stability of base levels and subsequently incised upon uplift. During each period of stability the hydrographic network was able to generate low-gradient, sinuous fluvial-karstic valleys. The phases of incision, on the other hand, radically modified the hydrographic network with the formation of *gorges* (water gaps) and wind gaps, flow inversions and major deviations due to fluvial piracy phenomena. Beheaded valleys are found up to 2100 m a.s.l. (Fig. 7a), and they are widespread on the paleosurfaces between 900 m and 1200 m.

During the phases of dissection, large volumes of siliciclastic deposits were conveyed to the far sink areas (i.e. the lower Volturno and Sangro valleys and coastal plains). As most of erosion localized on the siliciclastic rocks, the compressional and extensional lows entrapping them (previously called “corridors”) were emptied and the interposed limestone ridges developed marginal fault-line scarps up to hundreds of meters high. As regards denudation, interesting data come from the work of Corrado *et al*. (1998) who studied the unloading history of the Late Miocene – Lower Pliocene clays of Valle di Mezzo (E of the Meta-Mainarde thrust ridge) obtaining more than 1 km of exhumation since the Lower Pliocene.

A very important phase of incision and denudation seems the one occurred after the moulding of the Lower Pleistocene paleosurface at 1000-1200 m a.s.l.. Before the onset of this dissection phase, a poorly organized, low-gradient hydrographic network seems to have existed between Barrea and Montenero Val Cocchiara towns (Fig. 6), where the same phase of downcutting led the Sangro River to develop a more than 6 km long and up to 400 m deep gorge (Fig. 7b). This gorge suspended many S-flowing rivers from the northern portion of the aforementioned paleosurface and several SW-flowing rivers from its southern portion. Moreover, it captured several small endorheic basins. Another important water gap (about 300 m deep) is found where the Rio Colle Alto stream

cuts across Mt. Castelnuovo ridge, whose crest preserves also some wind gaps, testifying an ancient transversal drainage (Fig. 6, Fig. 7c): also this gorge probably formed between Lower and Middle Pleistocene.

The Lower Pleistocene paleosurface preserved in fragments around the Apennines main divide, generally hangs 200 m to 400 m over the present-day local base-levels. A considerable amount of dissection (150-200 m) also affects some glacial deposits occurring W of Mt. La Rocca and the travertines of Castel S. Vincenzo, both of Middle Pleistocene age and reduced to prominent outcrops by erosional relief inversion (Villani, 2005).

All this testifies for a generalized process of hydrographic network deepening, acting since

Lower-Middle Pleistocene times. In the Castel di Sangro alluvial plain (Fig. 5a and 6) fluvial terraces of presumable Middle-Late Pleistocene age stand 30 m to 50 m above the present thalweg, suggesting that this main phase of incision continued after the Middle Pleistocene with a roughly comparable rate.

The aforementioned erosional processes indeed enhanced local relief growth along the main tectonic escarpments, which put in contact resistant carbonatic bedrock and very erodible siliciclastic deposits. We believe that the E-facing escarpment of Meta-Mainarde massif was almost entirely exhumed by selective erosion during the Late Pliocene. During this time period, the several homoclines ridges of the area completed their exhumation from the ancient siliciclastic cover, leading to the appearance of steep fault-line scarps on their W and SW-facing slopes.

Incision of paleosurfaces and the consequent development of deep, steep flanked valleys (gorges) is here interpreted as the fluvial response to uplift. In our case, the hypothesis that such gorges may have originated by relative movements able to steepen the river profiles (*i.e.* tectonic coast retreat due to drowning of previously emerged marginal sectors; tectonic collapse of lower drainage-basin portions) can be rejected. In fact, since early Middle Pleistocene times, the uplift of the Late Pliocene – Lower Pleistocene foredeep deposits and the retreat of Adriatic coastline (about 30 km since Middle Pleistocene) have lengthened the Adriatic-flowing mainstreams. Furthermore,

the occurrence of localized Quaternary collapses is ruled out by the absence of both important faultscarps

and fluvial depocentres and the Pleistocene phase of incision appears to be generalized to the whole Axial and Peri-Adriatic Belts.

By our reconstruction of the MDA long-term geomorphological evolution it results that uplift had started at least since Lower Pliocene in response to thrusting, reaching maximum values in correspondence of Meta-Mainarde massif, which had already attained more than 1500 m of elevation before Pleistocene.

4 Discussion and conclusions

Previous studies attempting to reconstruct the long-term uplift history of the Central Apennines focused particularly on Quaternary events (better testified by stratigraphical markers from the chain marginal sectors) and considered the present-day elevation of the chain mainly due to Quaternary, large-scale uplift (see section 2). We therefore focus this final discussion on the Quaternary vertical movements inside the GVT, being aware that the rise and the morphoevolution of the Central Apennines inner portions started much earlier (Late Miocene – Lower Pliocene), and that both positive and negative motions have occurred since then, particularly in the Tyrrhenian flank of the chain (section 2).

In order to better reconstruct the amount and distribution of Quaternary uplift we critically reviewed the geological literature and enriched the data-set with the results of new geomorphological and morphometric analyses (chapter 3).

A possible, preliminary scheme of the cumulative Quaternary surface uplift in the study area is given in Fig. 8a. Areas presumably affected by comparable values of uplift were manually contoured, and the obtained values smoothed in order to get a rough, first-order picture of the regional uplift. In Fig. 8a the major Quaternary normal faults (associated scarps > 100 m) are also reported in order to visualize the possible control exerted by local tectonics in the spatial pattern of

uplift. Fig. 8b shows a comparison between the averaged values of Quaternary surface uplift and present-day elevation along the GVT.

Considered the lack of marine markers of ancient base levels in the internal portions of the Apennines, the preservation of paleosurfaces and paleovalleys up to the highest elevations is a fortunate case and a crucial source of information. First of all, the fact that a summit (or nearly so) paleosurface is still preserved on the ridges made of resistant carbonatic bedrock demonstrates that here the following denudation has been negligible. In the same while, the net erosion of the mountain belt was concentrated along the fault-bounded corridors exposing the much more erodible siliciclastic rocks, as confirmed also by stratigraphical and mineralogical data (section 3.3). Therefore, for those resistant ridges we can assume that rock uplift occurred after the shaping of their summit paleosurfaces roughly equates surface uplift. Furthermore, for the reasons given in section 3.3, the depth of incision nowadays affecting the Early Pleistocene paleosurface can be used as a proxy for the minimum value of Quaternary uplift.

To summarize our results on the Quaternary uplift of the study area, we move from the Tyrrhenian to the Adriatic coasts. Regarding the Peri-Tyrrhenian Belt, we preliminarily observe that it includes a southwestern sector that was affected by Plio-Quaternary extensional block faulting and, more to the NE, a sector substantially unaffected by such extension. Also the latter shows alternations of morphostructural highs and lows (mostly parallel to the chain axis), but passively influenced by ancient compressional features. In terms of Quaternary vertical movements, the southwestern sector displays a variable behaviour, with the coastal grabens being dominated by subsidence, the intervening horst suffering about 200 m of uplift and the Valle Latina remaining substantially stable. Starting from the Mt. Cairo Fault Zone, the northeastern sector shows evidence of about 400 m uplift that gave rise to a same amount of surface uplift of the carbonatic blocks, and was almost entirely compensated by downcutting in soft-rock corridors.

The quantification of Quaternary surface uplift in the Axial portion of GVT is made uncertain by the lack of Plio-Quaternary marine deposits and -for its eastern portion- of well preserved

paleosurfaces as well. Nonetheless, our geomorphological study has shown that this area did not suffer much tectonic fragmentation, fault scarps higher than 100 m being absent (Fig. 8a). So, the variability of surface uplift here is only due to unequal denudation (deepening of river valleys) superimposed on long-wavelength rock uplift. The excavation of valleys concentrated mostly on the more erodible, residual outcrops of the siliciclastic rocks. As the latter filled late Tertiary structural lows, several fault-line scarps up to a thousand meters high were formed.

As discussed in section 3.3, the Axial Belt suffered at least 400 m uplift during Quaternary times. At the transition with the Peri-Adriatic Belt, maximum values of about 700 m are reached, and they taper to zero towards the Adriatic coast. In the hypothesis that this tilting was linearly extended up to the Axial belt (rising it of about 1000 m), it should be assumed that the Early Pleistocene paleosurface of the MDA, which is nowadays at 1100 m, was formed at only hundred meters of elevation. This assumption appears unrealistic if the original distance from the coast (30 to 40 km) is considered. Therefore we conclude that the Axial belt rose some hundreds of meters less than the Peri-Adriatic one. In other terms we argue that the peak of Quaternary uplift in the GVT is shifted about 40 km to the NE of the chain axis. The spatial distribution of this uplift, in the Axial and Peri-Adriatic Belts together, forms a roughly symmetrical wave, about 90 km long (from the SW slope of Meta-Mainarde massif to the Adriatic coast; Fig. 8b).

Regarding style and amount of Quaternary uplift along GVT and their relations with topography, it appears that the characteristic wavelength of relief depicts the spatial pattern of surface uplift, short-wavelength components (15 km) of the Peri-Tyrrhenian side relying on high-angle faults periodicity. The long-wavelength components (over 40 km) of Axial and Peri-Adriatic sectors are on the other hand related to large-scale endogenic landmass inputs that obscured the single contributions of Pleistocene local offsets.

The pattern of regional surface uplift along GVT (Fig. 8b) seems to be the primary factor controlling the complex longitudinal profiles of the major Adriatic rivers (section 3.2). In particular,

the medium reach of the Sangro Valley (Fig. 4c), exhibiting a strong gradient, is supposed to be the response to a rapidly uplifting area.
By comparing the averaged value of Pleistocene cumulative surface uplift with the present-day mean elevation of the chain along GVT (fig. 8b), it results that major topographic growth of the Axial Belt took place mainly during pre-Quaternary times, when about 2/3 of the elevation were reached (section 3.3). The peak of Quaternary surface uplift, moreover, does not coincide with the overall bulk of averaged elevation in the Axial Belt (between 50 km and 90 km from the SW corner, along the GVT, fig. 8b), and suggests that the long-wavelength uplift of this sector of Central Apennines has migrated northeastwards through time, accordingly to some geodynamic models of the Apennines system (Doglioni, 1991; Cavinato and De Celles, 1999).

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Tables

Table 1

	Area	Hmean	Dispersion	skewness	E/R	Characteristic wavelength	Averaged relief range
Peri-Tyrrhenian Belt	4665 km^2	294 m	285 m	1.826	0.172	15 km	400 m
Axial Belt	8330 km^2	956 m	434 m	0.714	0.362	45 km	670 m
Peri-Adriatic Belt	3099 km^2	382 m	221 m	0.366	0.347	> 45 km	340 m

Table 2

River	Length	Hmax	Hmean	Average slope	Normalized integral of the profile
Volturno	133.4 km	690 m	166 m	0.0128	0.241
Liri	134.2 km	1242 m	338 m	0.0269	0.272
Sangro	125.4 km	1404 m	538 m	0.0720	0.383
Trigno	69.9 km	1339 m	322 m	0.1183	0.241
Biferno	94.1 km	1884 m	345 m	0.0363	0.183

Figure captions

Figure 1: Simplified geological map of the Central Apennines (modified, after: Miccadei, 1993; Scrocca and Tozzi, 1999). The black rectangle encloses the Gaeta-Vasto Transect (GVT). The white box encloses the Main Divide Area (MDA) described in section 3.3.

Figure 2: Topographic analysis of the study area: a) Contour map of elevation (from a 230-m DEM). The black solid line depicts the Apennines main divide, the dotted line indicates the subdivision of the Peri-Tyrrhenian, Axial and Peri-Adriatic Belts, the white rectangle encloses the GVT divide area and discussed in the followings; b) Map of averaged elevations. This map and the followings were obtained processing 230-m DEM using moving circular windows with 5 km radius; c) Map of dispersion of elevation; d) Map of E/R; e) relief change with sampling wavelength in the Peri-Tyrrhenian Belt; f) relief change with sampling wavelength in the Axial Belt; g) relief change with sampling wavelength in the Peri-Adriatic Belt.

Figure 3: Simplified hydrographic network of the study area. The main longitudinal valleys, transversal valleys, water gaps, elbows and endorheic areas are reported. Network belonging to the Sangro and Volturno rivers drainage basins is marked with a thicker brush.

Figure 4: Longitudinal profiles of five major rivers in the study area (from 90-m DEM): a) Volturno; b) Liri; c) Sangro (horizontal portions at 970 m and 250 m coincide with two artificial lakes); d) Trigno; e) Biferno. The five profiles have different horizontal and vertical scales.

Figure 5a: Simplified geological and morphostructural sketch of the MDA. The boxes refer to areas depicted in Figs. 7a-b-c. Terminology used in the is modified after: D'Alessandro *et al.*, 2003.

Figure 5b: Contour map of the MDA (contour interval: 100 m; from 230-DEM). The white line represents the Apennines main divide, which splits around a glacial trough (Meta-Mainarde massif, on the West) and a karstic basin (Montenero Val Cocchiara klippe, on the East).

Figure 6: Main structural and fluvial landforms in the MDA. The four major paleosurfaces groups are reported according to their age. Contour interval is 250 m.

Figure 7: Some examples of hydrographic network response to uplift in the MDA (images elaborated from the 90-m SRTM data; see location boxes in Fig. 5a): a) Hanging valleys on the Mainarde massif (view from N80, tilt 30°, artificial light 45° from SE, vertical exaggeration 1.5 x); b) The Sangro River water gap, between Barrea and Alfedena towns (view from N105, tilt 30°,

artificial light 45° from W, vertical exaggeration 1.5 x; c) The Rio Colle Alto water gap, near Castel S. Vincenzo town (view from N80, tilt 30°, artificial light 45° from NE, vertical exaggeration 1.5 x).

Nomenclature: *p*, paleosurface; *ds*, dip slope; *wtg*, water gap; *wg*, wind gap; *hv*, hanging valley; *bhv*, beheaded hanging valley; *flv*, fault-line valley.

Figure 8: a) Proposed scheme of the Pleistocene cumulative surface uplift along the GVT; b) Average elevation vs. Pleistocene surface uplift along the GVT.

Figure captions

Figure 1: Simplified geological map of the Central Apennines (modified, after: Miccadei, 1993; Scrocca and Tozzi, 1999). The white box encloses the area analyzed at 1:25000 scale and described in section 3.2.

Figure 2: Topographic analysis of the Gaeta-Vasto sector: a) Contour map of elevation (from a 230-m DEM). The black solid line depicts the Apennines main divide, the dotted line indicates the subdivision of the Peri-Tyrrhenian, Axial and Peri-Adriatic Belts, the white rectangle encloses the area analyzed at 1:25000 scale and discussed in the followings; b) Map of averaged elevations. This map and the followings were obtained processing 230-m DEM using moving circular windows with 5 km radius; c) Map of dispersion of elevation; d) Map of E/R.

Figure 3: Simplified hydrographic network of the study area. The main longitudinal valleys, transversal valleys, water gaps, elbows and endorheic areas are reported. Network belonging to the Sangro and Volturno rivers drainage basins is marked with a thicker brush.

Figure 4: Longitudinal profiles of five major rivers in the study area (from 90-m DEM): a) Volturno; b) Liri; c) Sangro; d) Trigno; e) Biferno. The five profiles have different horizontal and vertical scales.

Figure 5a: Simplified geological and morphostructural sketch of the Sangro-Volturno divide area. The boxes refer to areas depicted in Figs. 7a-b-c. For the terminology used in the legend (Cr1, Cr2, Cr3, Cv1, Cv2, Cb2, Pa) refer to: D'Alessandro et al., 2003.

Figure 5b: Contour map of the Sangro-Volturno divide area (contour interval: 100 m; from 230-DEM). The white line represents the Apennines main divide, which splits around a glacial trough (Meta-Mainarde massif, on the West) and a karstic basin (Montenero Val Cocchiara klippe, on the East).

Figure 6: Main structural and fluvial landforms in the Sangro-Volturno divide area. The four major paleosurfaces groups are reported according to their age. Contour interval is 250 m.

Figure 7: Some examples of hydrographic network response to uplift (from the 90-m SRTM data; see location boxes in Fig. 5a): a) Hanging valleys on the Mainarde massif (view from N80, tilt 30°, artificial light 45° from SE, vertical exaggeration 1.5 x); b) The Sangro River water gap, between Barrea and Alfedena towns (view from N105, tilt 30°,

artificial light 45° from W, vertical exaggeration 1.5 x; c) The Rio Colle Alto water gap, near Castel S. Vincenzo town (view from N80, tilt 30°, artificial light 45° from NE, vertical exaggeration 1.5 x).

Nomenclature: *p*, paleosurface; *ds*, dip slope; *wtg*, water gap; *wg*, wind gap; *hv*, hanging valley; *bhv*, beheaded hanging valley; *flv*, fault-line valley.

Figure 8: a) Proposed scheme of the Pleistocene cumulative surface uplift along the Gaeta-Vasto transect (the rectangle is the swath-profile covering the analyzed transect); b) Average elevation vs. Pleistocene surface uplift along the Gaeta-Vasto transect.

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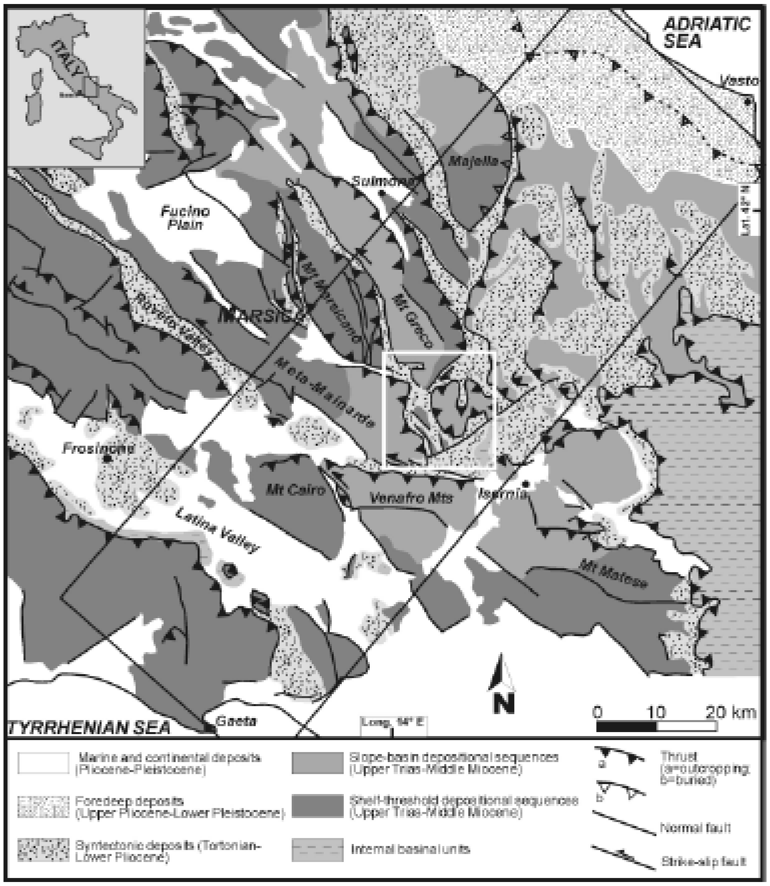

ADRIATIC SEA
ITALY
Vasto
Majella
Sulmona
Fucino Plain
MARSICA
Roveto Valley
Mt Marsicano
Mt Greco
Meta-Mainarde
Frosinone
Mt Cairo
Venafro Mts
Isernia
Latina Valley
Mt Matese
TYRRHENIAN SEA
Gaeta
N
0 10 20 km
Marine and continental deposits (Pliocene-Pleistocene)
Foredeep deposits (Upper Pliocene-Lower Pleistocene)
Syntectonic deposits (Tortonian-Lower Pliocene)
Slope-basin depositional sequences (Upper Trias-Middle Miocene)
Shelf-threshold depositional sequences (Upper Trias-Middle Miocene)
Internal basinal units
Thrust (a=outcropping; b=buried)
Normal fault
Strike-slip fault

Figure 1

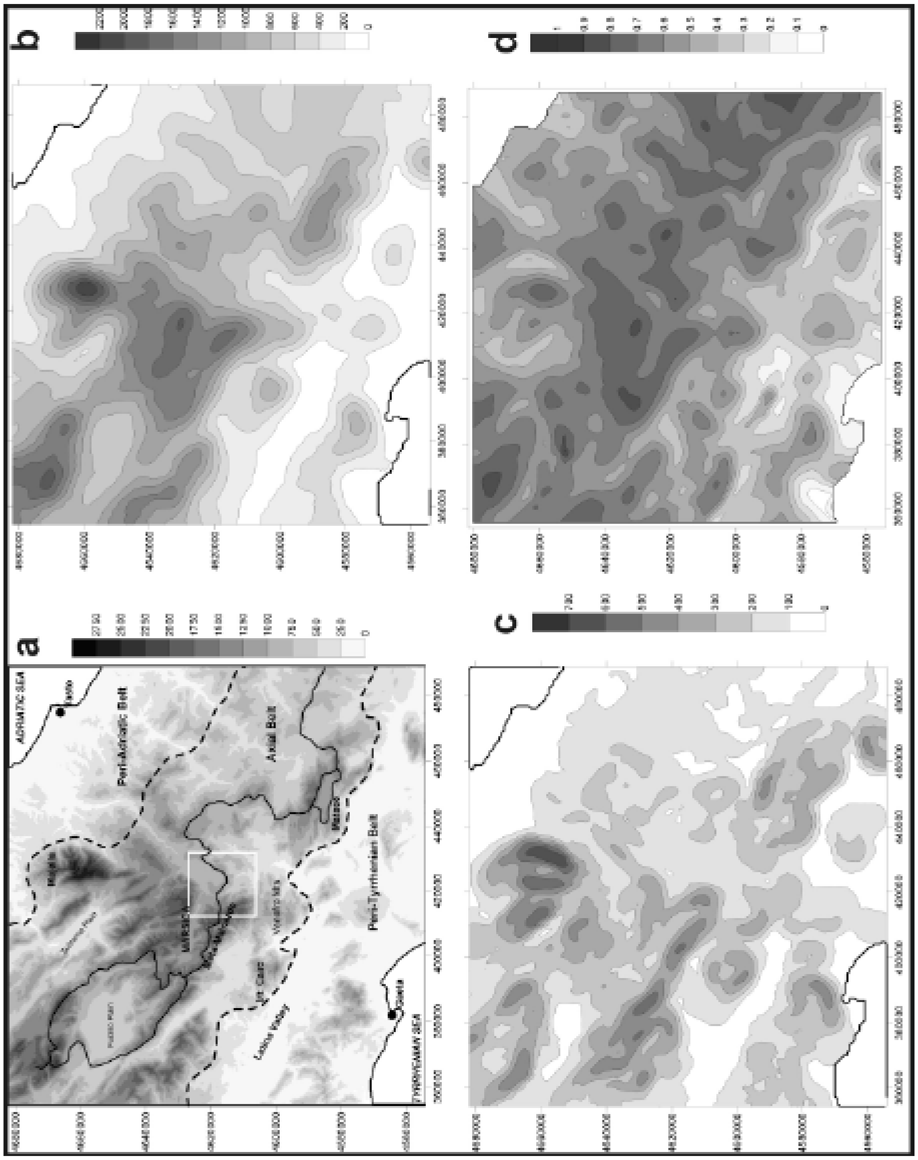


Figure 2

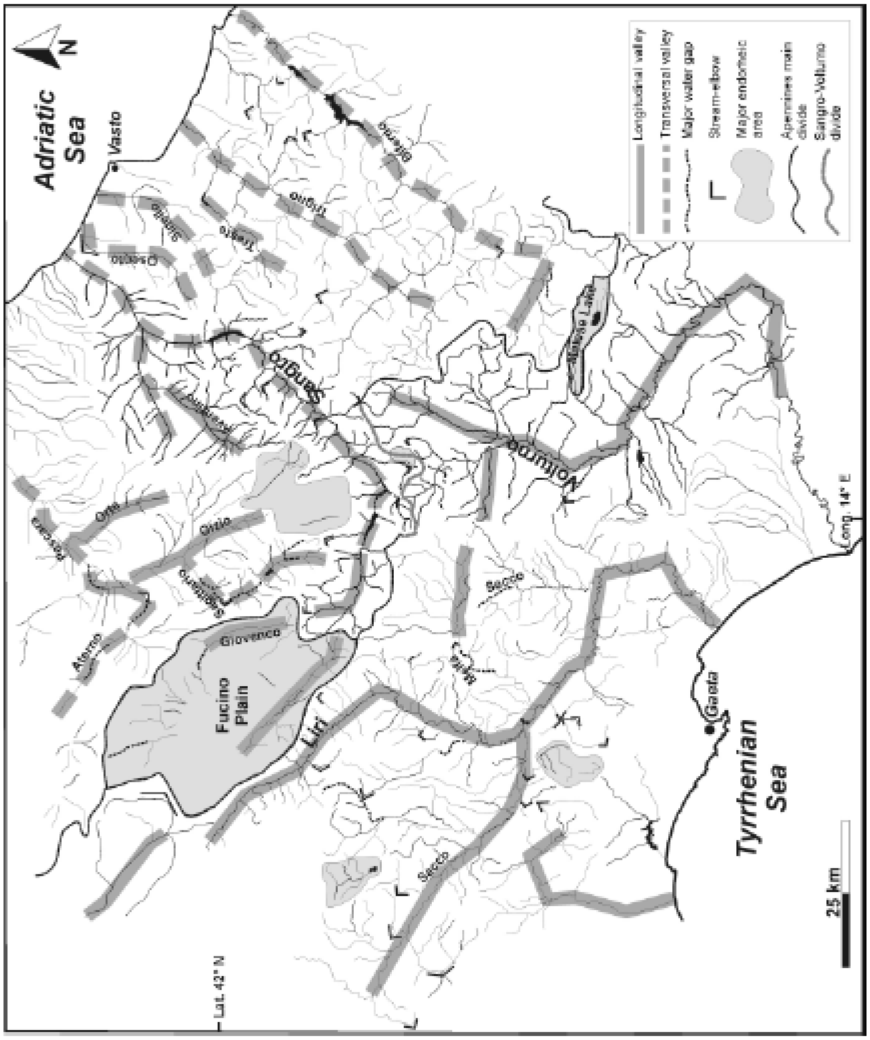
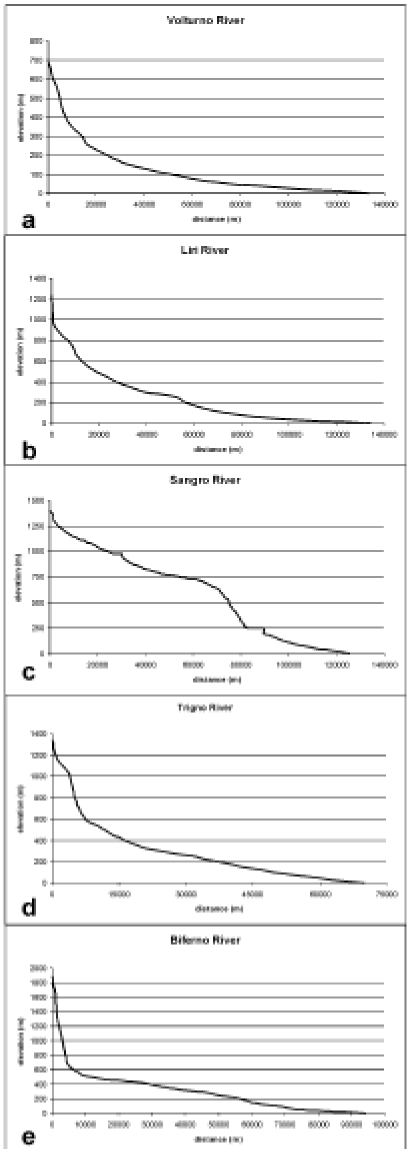

Adriatic Sea
Vasto
N
Longitudinal valley
Transversal valley
Major water gap
Stream-elbow
Major endorheic area
Apennines main divide
Sangro-Volturno divide
Sangro
Volturno
Fucino Plain
Giovenco
Liri
Aterno
Secco
Gaeta
Tyrrhenian Sea
25 km
Lat. 42° N
Long. 14° E

Figure 3



Volturno River
elevation (m)
distance (m)
a
Liri River
elevation (m)
distance (m)
b
Sangro River
elevation (m)
distance (m)
c
Trigno River
elevation (m)
distance (m)
d
Biferno River
elevation (m)
distance (m)
e

Figure 4

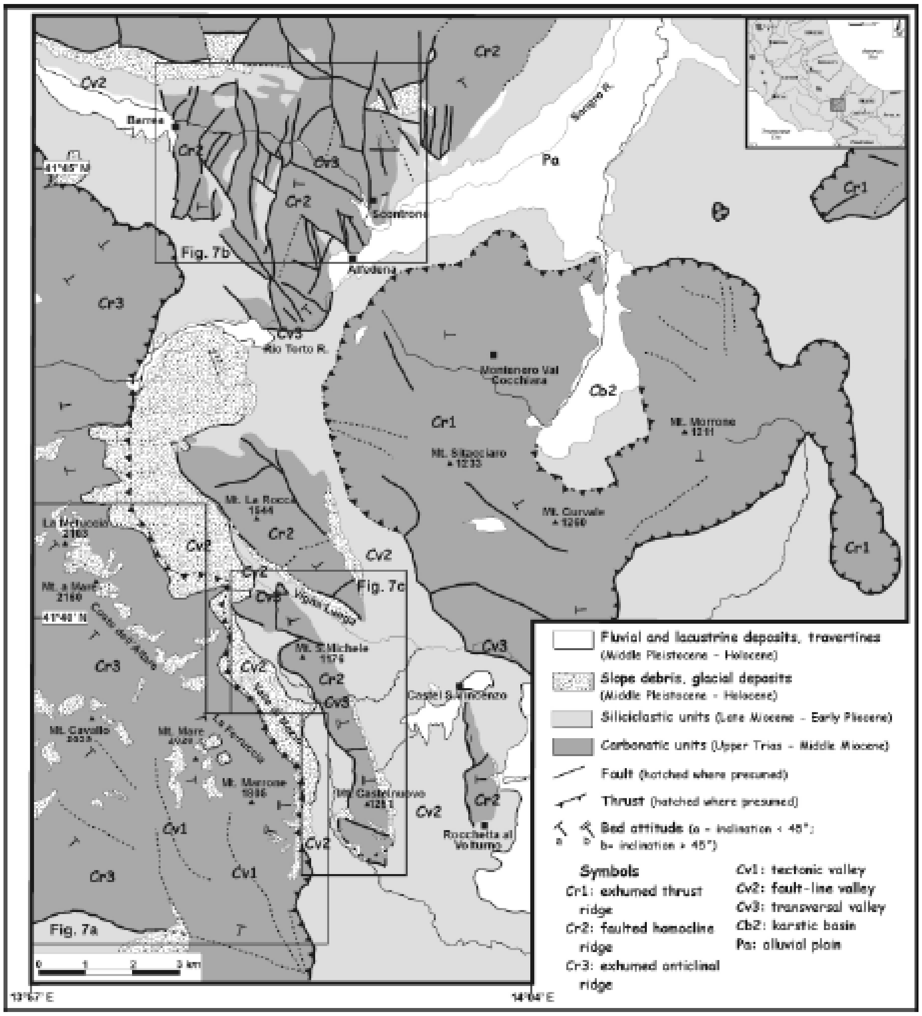


Fig. 7a
Fig. 7b
Fig. 7c
Cr1
Cr2
Cr3
Cv1
Cv2
Cv3
Cb2
Pa
Barrea
Scontrone
Alfedena
Rio Torto R.
Sangro R.
Montenero Val Cocchiara
Mt. Sitacciaro
Mt. Curvale
Mt. Morrone
Mt. Le Rocca
Mt. S.Michele
Mt. Castelnuovo
Castel S.Vincenzo
Rocchetta al Volturno
Mt. Cavallo
Mt. Marrone
Fluvial and lacustrine deposits, travertines (Middle Pleistocene - Holocene)
Slope debris, glacial deposits (Middle Pleistocene - Holocene)
Siliciclastic units (Late Miocene - Early Pliocene)
Carbonatic units (Upper Trias - Middle Miocene)
Fault (hatched where presumed)
Thrust (hatched where presumed)
Bed attitude (a = inclination < 45°; b= inclination > 45°)
Symbols
Cr1: exhumed thrust ridge
Cr2: faulted homocline ridge
Cr3: exhumed anticlinal ridge
Cv1: tectonic valley
Cv2: fault-line valley
Cv3: transversal valley
Cb2: karstic basin
Pa: alluvial plain
3 km
14°04' E

Figure 5a

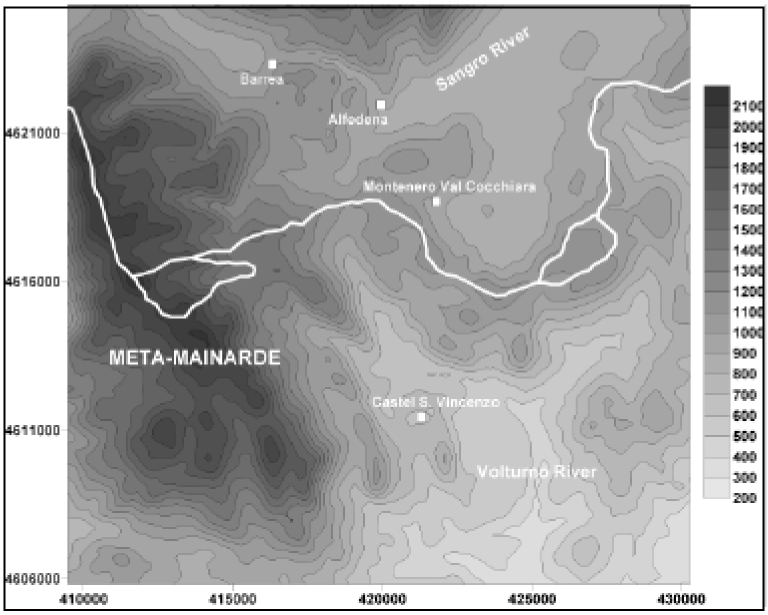

Sangro River
Barrea
Alfedena
Montenero Val Cocchiara
META-MAINARDE
Castel S. Vincenzo
Volturno River
4621000
4616000
4611000
4606000
410000
415000
420000
425000
430000
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200

Figure 5b

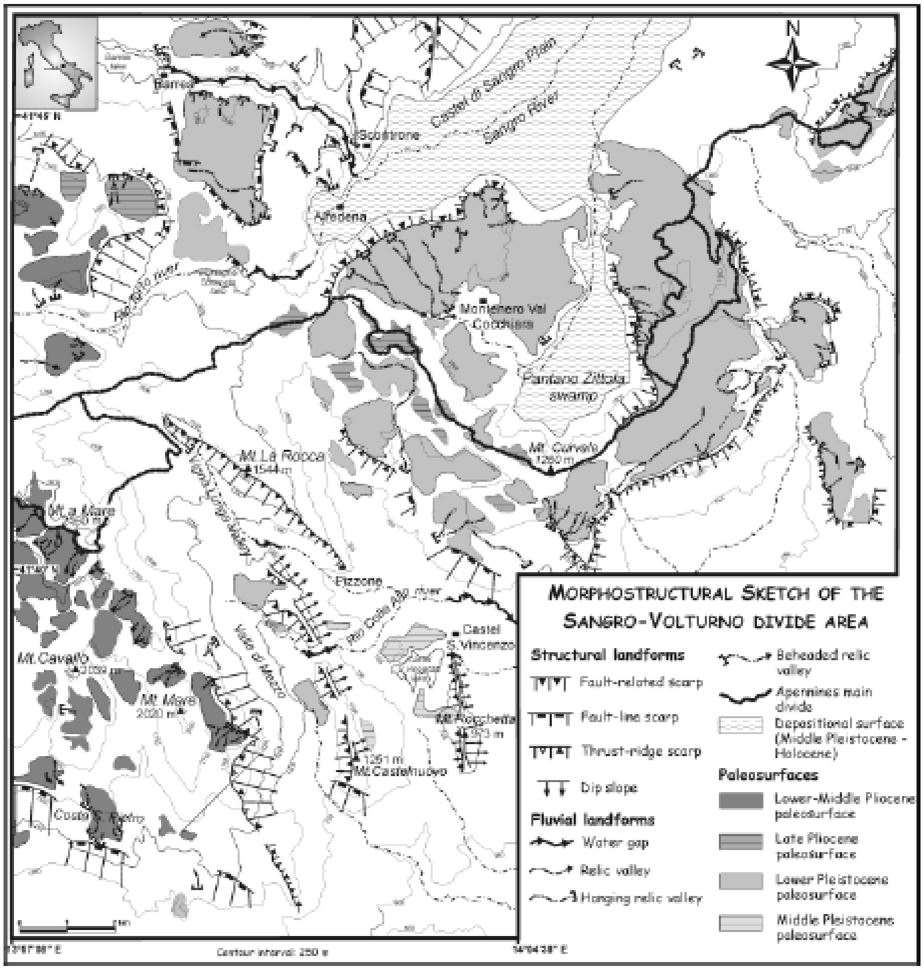
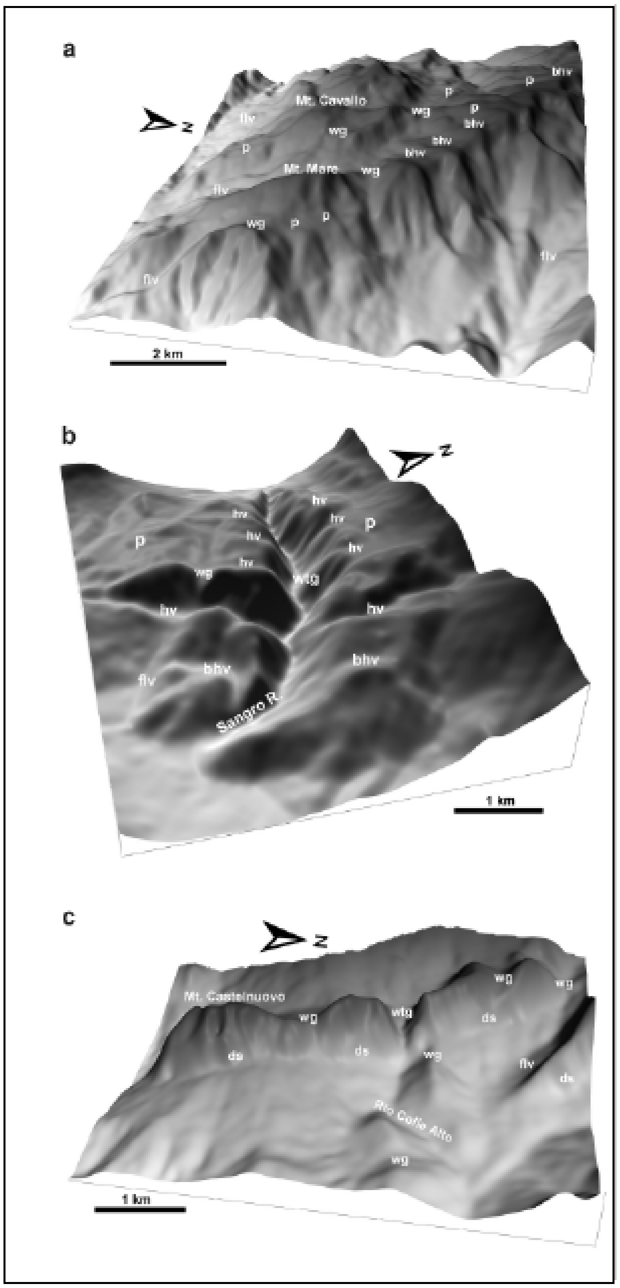

MORPHOSTRUCTURAL SKETCH OF THE SANGRO-VOLTURNO DIVIDE AREA
Structural landforms
Fault-related scarp
Fault-line scarp
Thrust-ridge scarp
Dip slope
Fluvial landforms
Water gap
Relic valley
Hanging relic valley
Beheaded relic valley
Apennines main divide
Depositional surface (Middle Pleistocene - Holocene)
Paleosurfaces
Lower-Middle Pliocene paleosurface
Late Pliocene paleosurface
Lower Pleistocene paleosurface
Middle Pleistocene paleosurface
N
Castel di Sangro Plain
Sangro River
Barrea
Scontrone
Alfedena
Montenero Val Cocchiara
Pantano Zittola swamp
Mt. Curvale
1260 m
Mt. La Rocca
1544 m
Mt. a Mare
Mt. Cavallo
Mt. Mare
2020 m
Pizzone
Castel S. Vincenzo
Mt. Rocchetta
1261 m
Mt. Castelnuovo
Costa S. Pietro
Valle di Mezzo
Contour interval: 250 m

Figure 6



a
Mt. Cavallo
N
flv
wg
p
bhv
Mt. Mare
2 km
b
N
hv
p
wg
wtg
bhv
flv
Sangro R.
1 km
c
N
Mt. Castelnuovo
wg
wtg
ds
flv
Rio Colle Alto
1 km

Figure 7

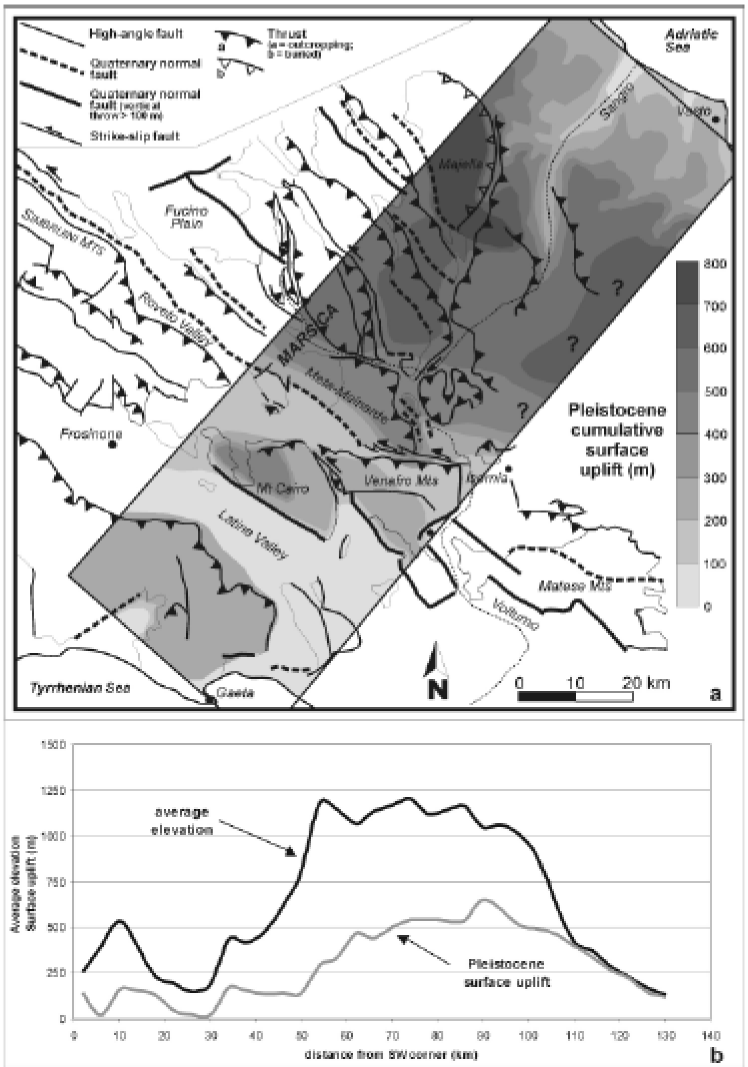

High-angle fault
Quaternary normal fault
Quaternary normal fault (vertical throw > 100 m)
Strike-slip fault
Thrust (a = outcropping; b = buried)
Adriatic Sea
Tyrrhenian Sea
Pleistocene cumulative surface uplift (m)
Majella
Sangro
Vasto
Fucino Plain
Simbruini MTS
Roveto Valley
MARSICA
Meta-Mainarde
Frosinone
Mt Cairo
Venafro Mts
Isernia
Latina Valley
Matese Mts
Volturno
Gaeta
N
0 10 20 km
a
average elevation
Pleistocene surface uplift
Average elevation Surface uplift (m)
distance from SW corner (km)
b

Figure 8a-b