Geogr. Fis. Dinam. Quat.
30 (2007), 13-32, 12 figg., 1 tab.

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MORPHOSTRUCTURAL SETTING OF THE SANGRO AND VOLTURNO RIVERS DIVIDE AREA (CENTRAL-SOUTHERN APENNINES, ITALY)

ABSTRACT: ASCIONE A., MICCADEI E., VILLANI F. & BERTI C., *Morphostructural setting of the Sangro and Volturno rivers divide area (Central-Southern Apennines, Italy)*. (IT ISSN 1724-4757, 2007).

Growth of topography in the Apennines has been driven by active tectonics (thrust-related crustal shortening and high-angle normal faulting related to crustal extension), regional rock uplift, and surface processes. Deep erosion has locally removed depositional growth strata leaving progressive unconformities genetically related to geomorphic features that can be used to interpret Apennine geologic history.

We present a geomorphic and morpho-structural analysis of an understudied, 400 km^2 part of the central-southern Apennines covering Abruzzo, Lazio, and Molise regions thought to have emerged during the Early Pliocene and been subjected to protracted, deep erosion since then. Our study reveals a high-relief landscape dominated by several morphostructures including high-standing, resistant Mesozoic and early Tertiary carbonates and intervening, erodible Tertiary siliciclastics. Quaternary deposits are few, scattered, and cannot generally be used for reconstructing paleo-base levels; however, this study defines and identifies several paleo-uplands and pediments that may be linked to paleo-base levels.

Cross-cutting relationships between the morphostructures, uplands, and pediments define the long-term geomorphic evolution of the area. Thrust and strike-slip faults were active only in the Miocene and Pliocene whereas the normal faults have been active during the Quaternary. The carbonate ridges were exhumed from the softer siliciclastics mostly in the Pliocene and a pre-Pliocene low relief upland was deeply incised. The base level fall driving this exhumation and incision is postulated to time the onset of regional rock uplift of the core of the southern Apennines to its present lofty mean elevation.

KEY WORDS: Morphostructure; Morphosculture; Paleosurface; Exhumation; Central-Southern Apennines.

RIASSUNTO: ASCIONE A., MICCADEI E., VILLANI F. & BERTI C., *Assetto morfostrutturale del settore di spartiacque Sangro-Volturno (Appennino centro-meridionale)*. (IT ISSN 1724-4757, 2007).

È stato condotto un dettagliato studio volto a definire l'assetto morfostrutturale e a ricostruire la storia morfoevolutiva di lungo termine di un'area vasta circa 400 km^2, situata tra il Lazio, l'Abruzzo e il Molise, a cavallo dello spartiacque appenninico, che in questo settore separa i bacini del Sangro e del Volturno.

Questo settore di catena, emerso sin dal Pliocene inferiore, è caratterizzato da un complesso assetto geologico e un forte rilievo locale. I depositi quaternari riferibili ad antichi livelli di base sono scarsi, e l'intero paesaggio è dominato da forme di erosione. Lo studio si è basato principalmente sull'analisi geomorfologica dei versanti strutturali e delle paleosuperfici. È stata riscontrata una prevalenza di forme controllate passivamente dalla struttura (morfosculture), con alti topografici, bordati da versanti su faglia, inscritti in rocce carbonatiche molto resistenti all'erosione, e bassi topografici incisi in rocce silicoclastiche, fortemente erodibili. La natura bipolare del substrato e l'erosione selettiva che ha agito su di esso sembrano essere la chiave della costruzione del rilievo durante il Quaternario nell'area di studio. Tra il Pliocene e il Pleistocene inferiore si sono avute le principali dislocazioni tettoniche, lo stesso intervallo di tempo durante il quale la gran parte dell'attuale elevazione assoluta dell'area è stata cumulata. Durante il Quaternario, invece, prevale una forte fase di erosione, responsabile di un forte incremento del rilievo locale. La morfodinamica quaternaria sembra essere la risposta a un generale sollevamento a largo raggio del settore assiale della catena appenninica centro-meridionale.

TERMINI CHIAVE: Morfostruttura; Morfoscultura; Paleosuperficie; Esumazione; Appennino centro-meridionale.

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The authors wish to sincerely thank F.J. Pazzaglia and an anonymous referee for the critical review of the paper and the useful comments that greatly improved the text. Stephen Monna is thanked for the useful suggestions on the English version of the manuscript and discussion on DEM analysis. Prof. L. D'Alessandro and L. Brancaccio are also thanked for the continuous spur on research. Work funded by MIUR grant (60% Faculty founds, 2006), L. D'Alessandro.

This work is the result of a research carried out by: A. Ascione and E. Miccadei (research guideline, geomorphological analyses), F. Villani (field geomorphological survey, morphometric analyses), C. Berti (field geomorphological survey and Quaternary stratigraphy). Synthesis of the geomorphological data, discussions and conclusions are the result of the collaboration of all the authors.

INTRODUCTION

The reconstruction of the long-term geomorphological evolution of the Apennines chain is a difficult task. In fact, topography of the Apennines range resulted from the combined action of tectonic displacements (related to thrusting and high-angle faulting), large-scale uplift and surface processes. The single contributions of these factors to the genesis of relief are hardly detectable. Furthermore, as thrusting and high-angle faulting arranged rocks of variable erodibility, differential erosion also played a major role.

This paper assesses the morphostructural setting of the Sangro and Volturno rivers divide area (the former flowing towards the Adriatic sea, the latter flowing towards the Tyrrhenian sea), in the axial belt of the Central-Southern Apennines. We aim to reconstruct the Pliocene-Quaternary morphotectonic evolution of the study area, namely the genesis of local relief by means of tectonics, erosion and large-scale uplift. We also try to give an approximate estimate of the cumulative vertical movement of the ground surface (*surface uplift*, England & Molnar, 1990) during the Pleistocene. We performed morphostructural and morphometric analyses, which were used to outline the main features of topography, the relationships between structural framework and physiography, and the roles played by tectonics and long-term (> 2 Myr) surface processes.

The clear distinction between exogenic and tectonic processes as concomitant factors in the building of orogenic relief, and their complex relationships on scale of millions of years (Schmidt & Montgomery, 1995; Howard, 1996; Kooi & Beaumont, 1996; Hovius, 2000; Osborn & *alii*, 2006), have recently been considered as a starting-point to study the large-scale geomorphology of the Apennines (see, among the others: Ascione & Cinque, 1999; Bartolini, 1999; D'Agostino & *alii*, 2001; Ascione & Cinque, 2003; Ascione & *alii*, 2003; Bartolini & *alii*, 2003; D'Alessandro & *alii*, 2003; Molin & *alii*, 2004; Molin & Fubelli, 2005; Spagnolo & Pazzaglia, 2005). The assessment of a large contribution of erosion in the genesis of mountainous relief, among others, has major implications in the estimation of vertical tectonic deformations and uplift rates, which could otherwise be overestimated or misinterpreted.

Morphostructural analysis provides a framework for the reconstruction of the surface evolution of thrust-belt interiors, where stratigraphical markers of surface uplift and tectonic displacements are generally quite rare or lacking (Burbank & Anderson, 2001). In the Sangro and Volturno rivers divide area the youngest marine deposits are strongly deformed synorogenic clays and sandstones (Miocene - Lower Pliocene in age). They crop out in deep depressions, hundreds or even thousands of meters below the adjacent ridge tops (exposing carbonate Mesozoic-Tertiary rocks). On the other hand, younger (Quaternary in age) continental deposits relatable to past base-levels are few and scattered.

In these unfavourable conditions, typical of mountainous settings, the morphostructural approach allows the recognition of the main structural, tectonic and erosional landforms, along with their relative chronology. We can reconstruct the main stages of landscape evolution that, in their turn, may be related to the causative erosional and/or tectonic processes. More in particular, by this approach reliable schemes of fault displacements and large-scale vertical movements of ground surface can be hypothesized. The result of our study is a tentative picture of Quaternary topographic growth of this sector of the Apennines.

Previous works on large-scale geomorphology of Central Apennines (see, among the others: Demangeot, 1965; Dramis, 1992; Coltorti & Pieruccini, 2000; D'Agostino & *alii*, 2001; Bartolini & *alii*, 2003; Pizzi, 2003) generally depict a strong (even more than 1000 m) uplift of the chain axis since Pleistocene times. Our estimates are more conservative. We briefly discuss the geomorphological and geological reasons of these results in the final section. On the other hand, we are aware of the intrinsic limits of the morphostructural method and discuss them in an appropriate section.

Many studies are available for the Quaternary extensional tectonics affecting adjacent regions to the N (*e.g.*: the middle-upper Sangro River Valley: Miccadei, 1993; Roberts & Michetti, 2004) and to the S (*e.g.*: the high Volturno Valley and the Matese massif: Brancaccio & *alii*, 1997; 2000; Corrado & *alii*, 1997; Cinque & *alii*, 2000 and references therein). There are only few studies about Pliocene-Quaternary tectonics and geomorphology of the Sangro and Volturno rivers divide area (e.g.: Damiani & Pannuzi, 1980). One of our objectives is to clarify the Quaternary tectonics of this region.

METHODS

Our study mainly consisted in combined morphometric and morphostructural analyses.

As regards morphometry, we used SRTM elevation data for spatial analysis of topography, following some standardized procedures described in many papers (see, among the others: Klinkenberg, 1992; Guzzetti & Reichenbach, 1994; Weissel & *alii*, 1994 and references therein). The SRTM height files were first converted in a WGS84 projection and the latitude/longitude values were transformed in UTM coordinates, then we created a regular 90-m grid of elevation data. We focus on the first-order quantitative properties of topography, so the main features of landscape (high-order valleys, ridges, hillslopes, low-relief surfaces etc.) are still satisfactorily represented by such a coarse grid.

We calculated statistical parameters of elevation data (maximum, minimum and mean values, standard deviation, skewness), their frequency distribution (elevation data were divided into height intervals of 50 m, and for each interval the number of data was extracted) and hypsometric indices (elevation/relief ratio, E/R). High values of dispersion depict a rugged topography (Klinkenberg, 1992). High values of E/R, together with right-skewed frequency distribution of elevation, can be related to low values of erosion, and possibly depict landscapes preserving high-standing low relief surfaces. We also analyzed the relationships between average slope and elevation. The elevation data were divided into height intervals of 50 m and for each interval the average terrain slope was computed. The trend of a slope vs. elevation curve depicts the vertical distribution of hillslopes and low relief surfaces. A decrease in average slope with increasing elevation, not so common in mountainous settings (see, among the others: Schmidt & Montgomery, 1995; Kühni & Pfiffner, 2001; Bishop & *alii*, 2002), is indicative of some high-standing low relief surfaces, and requires a geomorphological explanation. Our discussion about average slope is exclusively restricted to its relationships with altitude. We leave out of consideration absolute values of slope, because they obviously depend on DEM resolution.

We carried out morphostructural analyses through careful inspection of topographic maps (1:25000 and 1:10000 scale) and aerial photos (1:33000 scale, Volo Regione Abruzzo, 1990), and through field surveys.

Our goal is discerning the roles of tectonics and erosion in the genesis of local relief. We therefore first focused on the following main points: 1) analysis of fault slopes, discriminating between slopes created by tectonics (*i.e.*: fault scarps), slopes created by differential erosion of rocks on either side of the fault (*i.e.*: fault-line scarps) or by the mixed action of differential erosion and fault slippage (*i.e.*: fault-related scarps); 2) analysis of structural landforms due to the attitude of bedrock strata and intervening erosional processes (*morphosculptures*, for example: dip-slopes, hogbacks, mesas, etc.). We then grouped the main structural landforms in few basic categories, following a scheme proposed by D'Alessandro & *alii* (2003) and discussed in an appropriate section.

The recognition of ancient base-levels and related landforms is fundamental for constraining estimates of surface uplift. We therefore focused on the following points: 1) analysis of erosional/depositional fluvial and lacustrine terraces and their amount of incision; 2) analysis of relic erosional landsurfaces (hereinafter named *paleosurfaces*); 3) analysis of hydrographic network and its relationships with morphostructures.

Paleosurfaces (also said *gentle erosional landform*s in Amato & Cinque, 1999, or *low relief landscapes* in Ascione & Cinque, 1999) play a major role in our study. They are relics of ancient, hanging, low-relief erosional landscapes carved on bedrock, generally preserving beheaded and/or truncated, low-gradient paleovalleys, which now are completely isolated from the present-day hydrographic network. Paleosurfaces are typically found on summit areas, but they can form nested systems, deeply entrenched in mountainous settings. Paleosurfaces indicate the occurrence of periods during which the erosional processes (mainly fluvial and karstic planation) smoothed the relief created by thrust belt accretion. Estimation of the original elevation a.s.l. of a paleosurface carved on Mesozoic-Tertiary bedrock is also difficult or even impossible. However, the present elevation of these high-standing landforms may be related only to local offsets or to large-scale uplift, due to regional evidences of their clear involvement in the Pliocene - Lower Pleistocene accretion of the Central-Southern Apennines and subsequent Quaternary uplift (Amato & Cinque, 1999; Coltorti & Pieruccini, 2000). Paleosurfaces have been regarded as the only available markers of long-term (*i.e.*: Pliocene-Quaternary), large-scale topographic growth in this sector of the Central Apennines.

The age estimation of paleosurfaces is a difficult task. Paleosurfaces on summit areas (above 1500-1700 m a.s.l.) have a wide distribution in the Abruzzi Apennines, and many Authors have dated them back to the Pliocene (see also: Bosi & *alii*, 1996; Galadini & *alii*, 2003). In our study, we used geomorphological correlations with known deposits and landforms. We mapped the Quaternary continental deposits relatable to past local base-levels (travertines, fluvial gravels and lacustrine clays) or well known Pleistocene climatic fluctuations (glacial till; see a chronological framework in: Giraudi, 2003). We then made a relative chronology scheme of the tectonic and erosional events by means of cross-cut relationships between structural, erosional and depositional landforms. Due to the lack of absolute dating of the aforementioned continental deposits, our age estimates of paleosurfaces and other landforms are merely relative. Nonetheless, we tried to fit our reconstruction with a reliable geological framework of this sector of the Apennines (Patacca & *alii*, 1992; Scrocca & Tozzi, 1999; Bosi & *alii*, 2003; D'Alessandro & *alii*, 2003).

We finally estimated the magnitude of large-scale vertical movement of the ground surface during the Pleistocene. Our assumption is that the degree of fluvial incision of the paleosurfaces in the study area roughly equates their surface uplift (see, for example: Amato & Cinque, 1999; Johansson & *alii*, 1999; Coltorti & Pieruccini, 2000; Boenzi & *alii*, 2003; Sobel & Strecker, 2003, etc.).

GEOLOGICAL AND STRUCTURAL SETTING

The study area is located S of Mt. Greco ridge and N of Venafro Mts., between 41°45' - 41°36' N latitude and 13°57' - 14°09' E longitude (figs. 1a, 1b). This portion of the Apennines chain is located at the junction of the two major northern and southern Apenninic arcs (Patacca & *alii*, 1990), and was accreted between Late Miocene and Pliocene with NE sense of transport. Following accretion, regional emersion and tilting of the Central-Southern Apennines foredeep took place, leading to a gradual eastwards shift of the Adriatic coastline (Cinque & *alii*, 1993). Several thrust sheets related to different paleogeographic domains define a complex structural setting (D'Andrea & *alii*, 1992; Patacca & *alii*, 1992; Di Bucci & *alii*, 1999; Scrocca & Tozzi, 1999). These thrust sheets consist of Mesozoic-Tertiary carbonates and Late Miocene - Lower Pliocene siliciclastics. Their original stratigraphical and geometrical relationships were severely obliterated by repeated tectonic deformations, occurred until the Late Pliocene (Patacca & *alii*, 1992; Miccadei, 1993; Corrado & *alii*, 1997). Siliciclastics are in fact almost everywhere decoupled from their original carbonate basement. These thrust sheets now form a complex stack that is offset by N-S, E-W and WSW-ENE trending normal and strike-slip faults (fig. 1a).

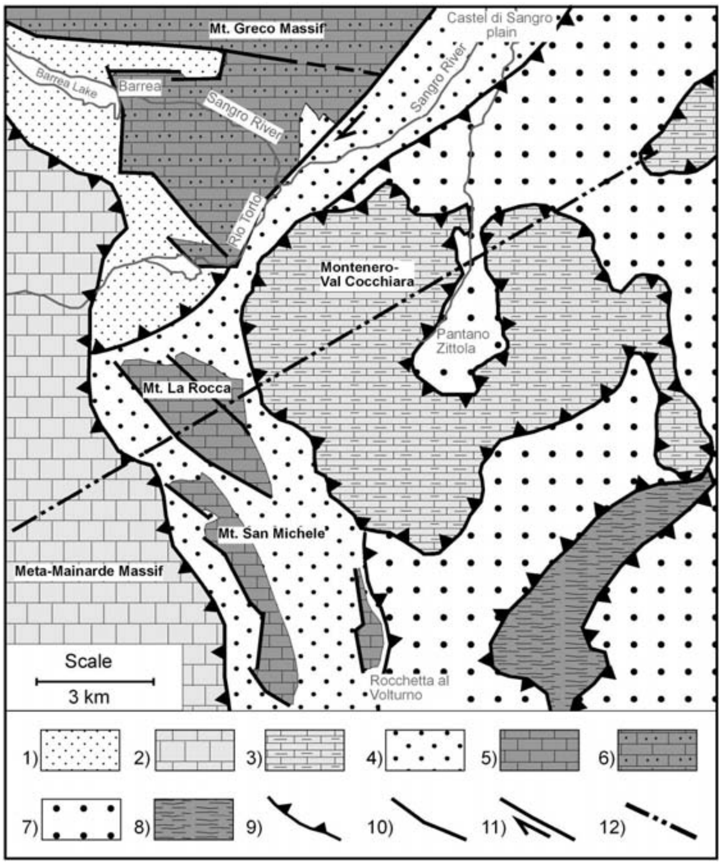


FIG. 1a - Structural scheme of the study area (Patacca & Scandone, 1989; Di Bucci & *alii*, 1999). Latium-Abruzzi Carbonate Platform Unit: 1) siliciclastic deposits (Late Miocene); 2) by-pass margin carbonates (Triassic - Miocene; 3) slope to basin carbonates (Jurassic - Miocene). Apulian Carbonate Platform Unit; 4) siliciclastic depodits (Late Miocene - Pliocene); 5) shelf carbonates (Jurassic - Miocene); 6) slope carbonates (Cretaceous - Miocene). Molisan Units; 7) siliciclastic deposits (Late Miocene); 8) multicoloured clays (Oligocene. Miocene); 9) Thrust; 10) dip-slip fault; 11) strike slip fault; 12) trace of cross section (fig 3a).

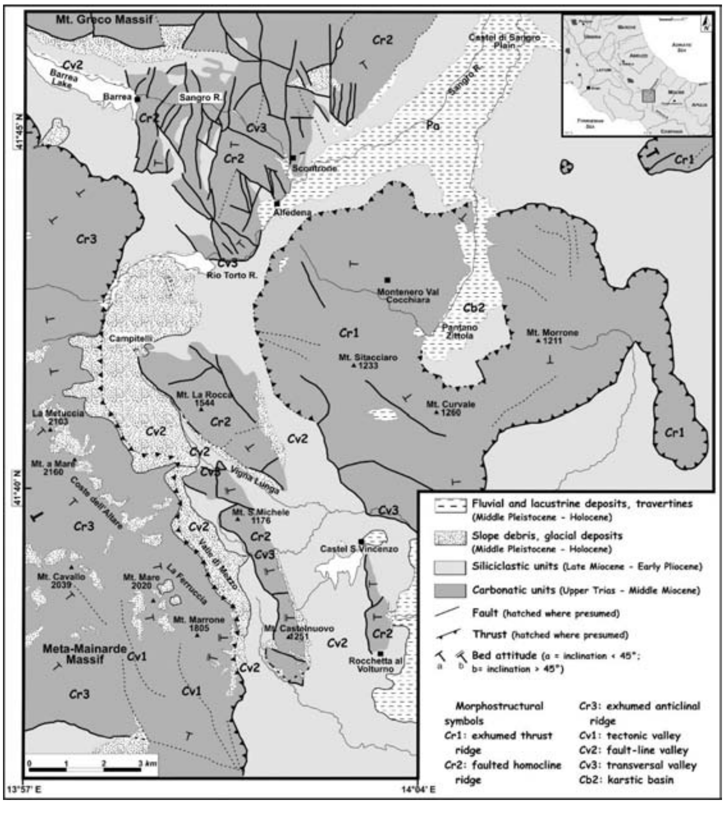


FIG. 1b - Simplified morphostructural map of the study area (modified from D'Alessandro & *alii*, 2003).

The westernmost Meta-Mainarde thrust sheet is composed of a thick pile (more than 2000 m) of Late Triassic to Middle Miocene carbonate rocks, deposited in a slope-to-basin setting (Patacca & Scandone, 1989; Miccadei, 1993). The Meta-Mainarde thrust sheet, which is the highest one (both topographically and structurally) in the study area, is folded into a broad anticline. It is bordered to the E by a N-S trending thrust with a generally E-ENE slip direction (Miccadei, 1993), and by a strike-slip fault system on the southern side (Scrocca & Tozzi, 1999) (fig. 1a).

Similarly, the Montenero Val Cocchiara klippe (Di Bucci & Scrocca, 1997), which crops out in the central and eastern portions of the study area, is made up of more than 300 m Lower Cretaceous to Middle Miocene carbonates. Some hundreds meters of Late Miocene siliciclastics crop out on the northern edge of the klippe, above the Middle Miocene carbonates (Patacca & *alii*, 1992; Di Bucci & Scrocca, 1997). This thrust sheet shows a general N sense of transport over the siliciclastics (Di Bucci & Scrocca, 1997) (fig 1a).

The deepest structural unit in this portion of the chain crops out in correspondence of the Mt. La Rocca, Mt. S. Michele and Mt. della Rocchetta ridges. It is related to the Apulia platform, involved in the Pliocene thrusting of the Central-Southern Apennines (D'Andrea & *alii*, 1992; Patacca & *alii*, 1992; Di Bucci & *alii*, 1999; Scrocca & Tozzi, 1999; fig. 1a). These ridges are underlain by more than 300 m Late Jurassic (Lower Cretaceous in the case of Mt. della Rocchetta) to Middle Miocene inner shelf carbonates. This carbonate section is followed by Late Miocene - Lower Pliocene siliciclastics. Their lower portion consists of a monotonous pack of clay and generally thin bedded sandstone, at some places interrupted by wide olistostromes of Cretaceous marls and cherts. These deposits are more than 2000 m thick (Fonteviva-1 well, on the eastern edge of Montenero Val Cocchiara klippe; Scrocca & Tozzi, 1999). The aforementioned ridges are bordered by high angle faults on their W and SW sides. To the S, the Mt. S. Michele and Mt. della Rocchetta ridges are bordered by NW-SE and SW-NE trending strike-slip faults (Scrocca & Tozzi, 1999).

The southern termination of the Mt. Greco thrust sheet crops out N of the Meta-Mainarde massif, between the Sangro and Rio Torto valleys. It is composed of a more than 400 m thick section of carbonate slope deposits, Lower Cretaceous to Late Miocene in age (Mattei & Miccadei, 1991; Miccadei, 1993; fig. 2). In the Scontrone area, a Late Miocene continental vertebrate fauna is reported (Patacca & *alii*, 2006). It testifies for the presence of wide emerged areas since the Late Miocene. This unit is bordered to the S by a SW-NE trending dextral strike-slip fault (*Alfedena Fault*: Mattei & Miccadei, 1991; Miccadei, 1993).

As regards siliciclastics, studies (Corrado & *alii*, 1998) about the tectonic burial and erosional exhumation of the upper clayey members from the southern termination of the Valle di Mezzo and around the southern edge of the Montenero Val Cocchiara klippe, show that these rocks underwent several hundreds meters of exhumation since the Lower Pliocene.

In the study area the continental deposits are generally few and scattered (fig. 2). The widest outcrops are represented by the Middle-Late Pleistocene glacial deposits resting at the piedmont of the Meta-Mainarde massif (Cinque & *alii*, 1990; Jaurand, 1998; Giraudi, 2003). Along the E and S borders of Mt. della Rocchetta, at the Volturno river springs, a thick travertine plate crops out: its maximum age is about 70 kyr, according to ^{230}Th analyses (Brancaccio & *alii*, 1988). The Sangro River Valley, between Alfedena and Castel di Sangro, hosts Late Pleistocene to Recent alluvial deposits, just about 20 m thick (Miccadei, 1993; Capelli & *alii*, 1998).

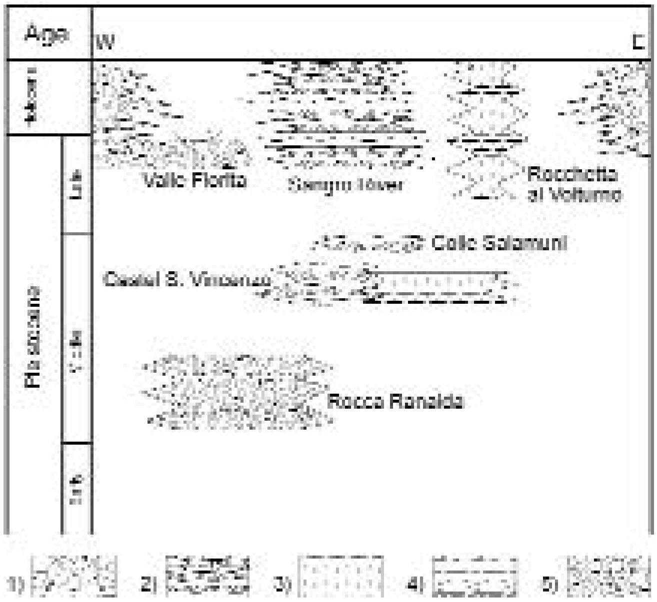


FIG. 2 - Stratigrafic scheme of Quaternary deposits outcropping in the study area (Brancaccio & *alii*, 1988; Giraudi, 1997; Capelli & *alii*, 1998). 1) slope deposits; 2) conglomerates; 3) travertine; 4) lacustrine deposits; 5) moraine. Time axis not in scale.

In this paper we discuss the aforementioned continental deposits and we add new data about some small outcrops, with the aim of unravelling the evolution of hydrographic network in the study area and its possible relationships with uplift.

PHYSIOGRAPHY AND TOPOGRAPHY

The study area is generally mountainous, particularly in its western portion (figs. 3a, 3b, 4a). The main physiographic feature is represented by the Meta-Mainarde massif, with several peaks exceeding 2000 m. a.s.l. (from N to S: Mt. Tartaro, 2191 m; Mt. Petroso, 2249 m; Mt. Meta, 2242 m; Mt. Metuccia, 2102 m; Mt. a Mare, 2160 m; Mt. Cavallo 2039 m; Mt. Mare 2020 m). The massif is bordered to the E by the narrow and deep Valle di Mezzo, oriented in a N-S direction. To the N, this valley is bordered by the NW-SE trending Mt. La Rocca ridge (1544 m), while to the E the N-S trending Mt. S. Michele (1176 m) and Mt. della Rocchetta (973 m) ridges are present (fig. 1b).

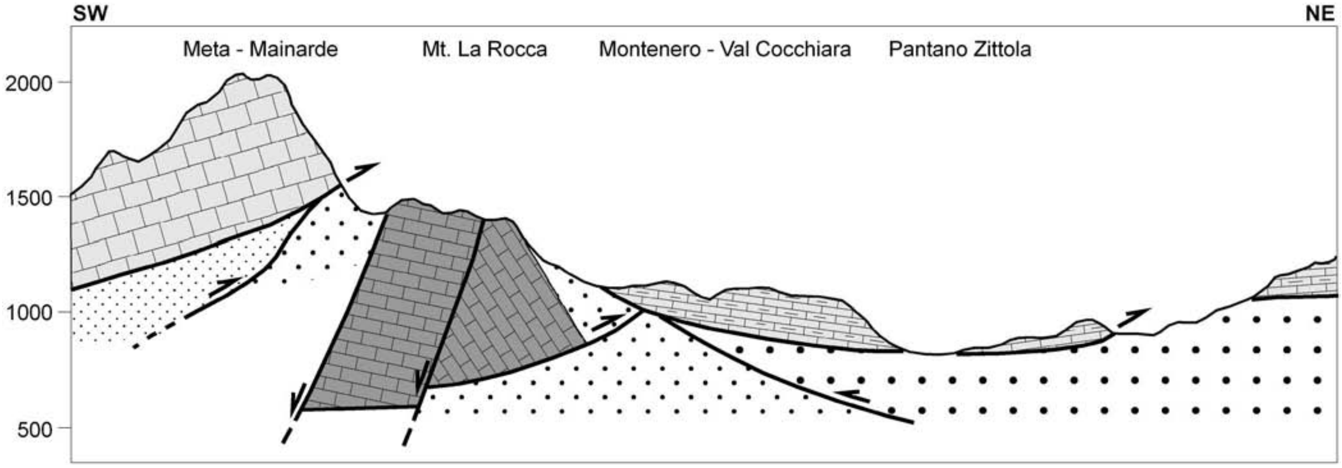


FIG. 3a - Simplified geological cross-section (see fig. 1a for legend).

FIG. 3b - Panoramic view of the main physiographic units in the western part of the cross-section shown in fig 3a. On the background, the eastern escarpment of Meta-Mainarde massif; then, on the right the NE escarpment of Mt. La Rocca ridge and, to the left, the eastern escarpment of Mt. S. Michele ridge; on the foreground, the eastern escarpment of Mt. della Rocchetta ridge and the Castel San Vincenzo travertines plate.

In the study area, the Apennines main divide (which coincides with the Sangro and Volturno rivers divide) has an average elevation of about 1300 m a.s.l. It has a N-S orientation on the highest peaks of the Meta-Mainarde massif (fig. 4a), then it abruptly turns to the E and descends for about 1000 m towards the hills of the Campitelli area (W of Mt. La Rocca) and the hills surrounding Montenero Val Cocchiara (at about 1100 m a.s.l.). There the landscape is characterized by small, smooth, isolated tops and very large interfluves with gentle slopes. North of the Apennines main divide (*i.e.* in the Adriatic sector of the study area) and S of the Mt. Greco massif, there are two main physiographic features: from W to E, a gently hilly landscape, dissected by the deep and narrow Sangro River gorge (between Barrea and Alfedena), stands about 300 m higher than the adjacent, wide and flat Castel di Sangro Plain.

In the western portion of the study area, the valleys cross-section is generally V-shaped and their width is very small (1 km or less) if compared to the interfluves spacing (some kilometers in the Meta-Mainarde massif). In the eastern portion the valleys become wider with gentler slopes, but still interfluves retain noticeable width (especially on the Montenero Val Cocchiara klippe). The only exception is represented by the Mt. La Rocca, Mt. S. Michele and Mt. della Rocchetta sharp and narrow ridges.

Topographic properties of the study area were computed from a 90-m DEM and they are summarized in table 1. The average elevation is higher than 1000 m. The frequency distribution of elevation data (fig. 4b) is roughly symmetrical (skewness is 0.543) and platykurtic (kurtosis is −0.408). It shows that the bulk of topography (about 43%) is sited between 800 m and 1150 m a.s.l. (with a modal peak at 801-850 m elevation class). This is also con-

TABLE 1 - Main statistical and morphometric parameters of the Sangro-Volturno divide area (data from 90-m DEM)

Hmax	Hmin	Hmean	dispersion	skewness	kurtosis	E/R
2194 m	295 m	1085 m	411 m	0.543	-0.408	0.416

firmed by quite high dispersion (standard deviation is 411 m). The normalized hypsometric curve, with a slight concave-up shape, is shown in fig. 4c (E/R is 0.416).

The relationships between average slope and elevation are shown in fig. 4d. Absolute values of slope are merely indicative, due to their strong dependence on DEM reso-

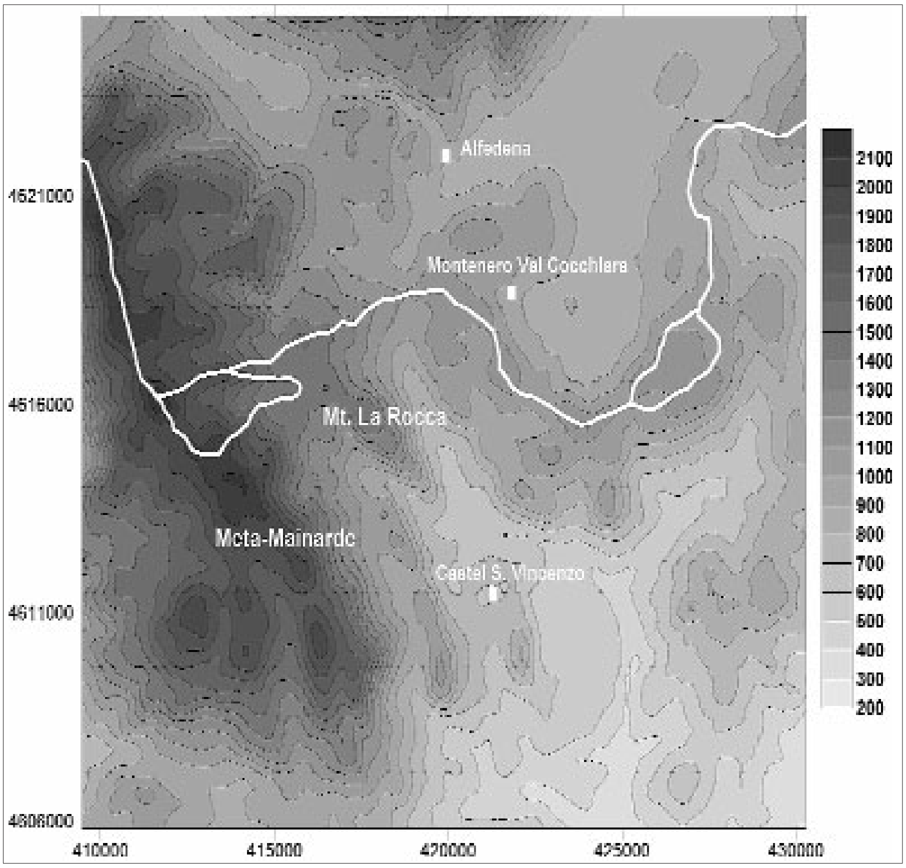


FIG. 4a - Contour map of the study area, from the 90-m DEM (100 m contour interval). The white line indicates the Apennines main divide (here separating the Sangro and Volturno rivers drainage basins). Some major endorheic areas along the divide are found at a glacial trough outlet (Meta-Mainarde massif), on the W, and in a karstic basin (Montenero Val Cocchiara klippe), on the E. See details in the text.

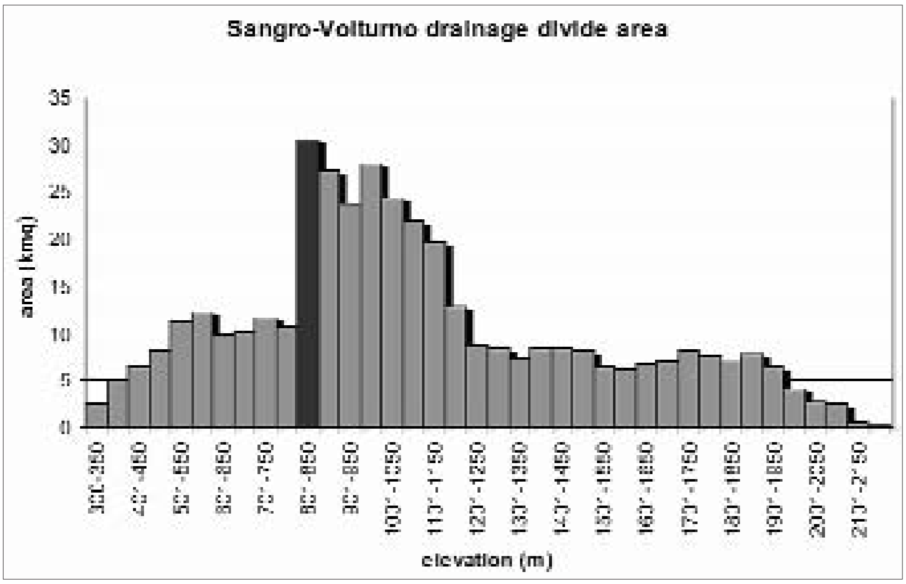


FIG. 4b - Elevation histogram of the study area (data from the 90-m DEM).

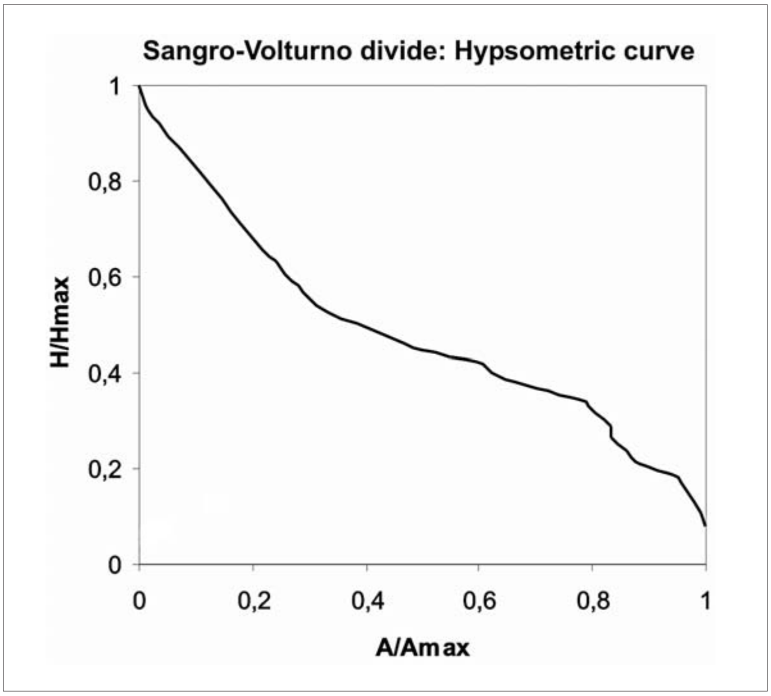


FIG. 4c - Hypsometric curve of the study area. Cumulative values of area-altitude pairs are normalized with respect to the maximum planar area (404.9 km^2) and maximum elevation (2194 m) according to elevation data of 90-m DEM.

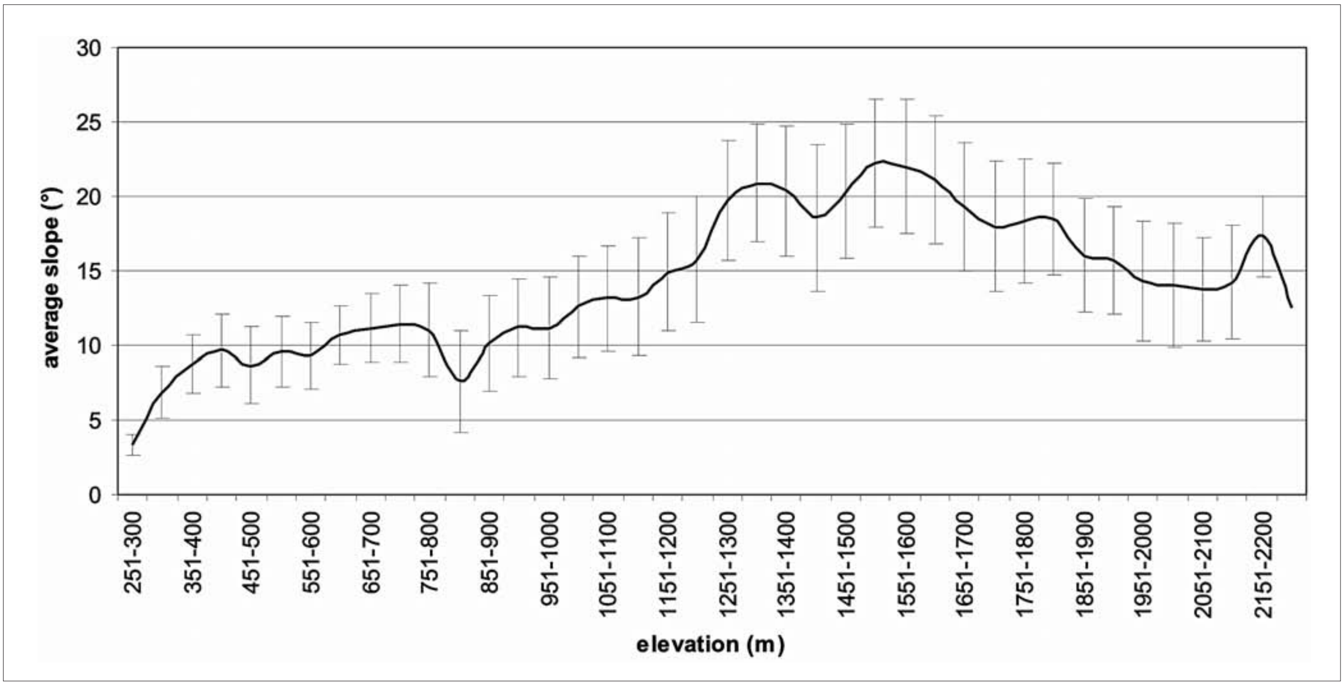


FIG. 4d - Average slope vs. elevation curve (the error bars indicate standard deviation of slope values for each 50-m elevation class). Data from 90-m DEM. See details in the text.

lution, and they are not took into consideration in our discussion. The curve initially shows a gradual increase in average slope with elevation, but after a sort of threshold (about 20°-22°, between 1350 m and 1700 m), the average slope clearly decreases, reaching a local minimum (about 12°-14°) between 1850 and 2100 m. Therefore, at high altitudes a negative correlation between average slope and elevation can be envisaged. Furthermore, the curve shows some other subtle relative minima (at 801-850 m, 951-1000 m, 1101-1150 m, 1401-1450 m, 1701-1750 m) which in part correspond to the secondary modal peaks of the frequency distribution of elevation (fig. 4b). Both of these aspects are clearly related to the presence of several sets of low relief surfaces that occur also on the summit areas (Meta-Mainarde massif and Montenero Val Cocchiara surroundings).

MORPHOSTRUCTURAL SETTING

In this section we describe the salient geomorphological and morphostructural elements of the study area, following the geographical distribution of the main physiographic units. The collected data have been in part synthesized in a simplified morphostructural map (fig. 5).

The Meta-Mainarde massif

The study area includes just the eastern portion of the Meta-Mainarde massif. It is part of the western Marsica

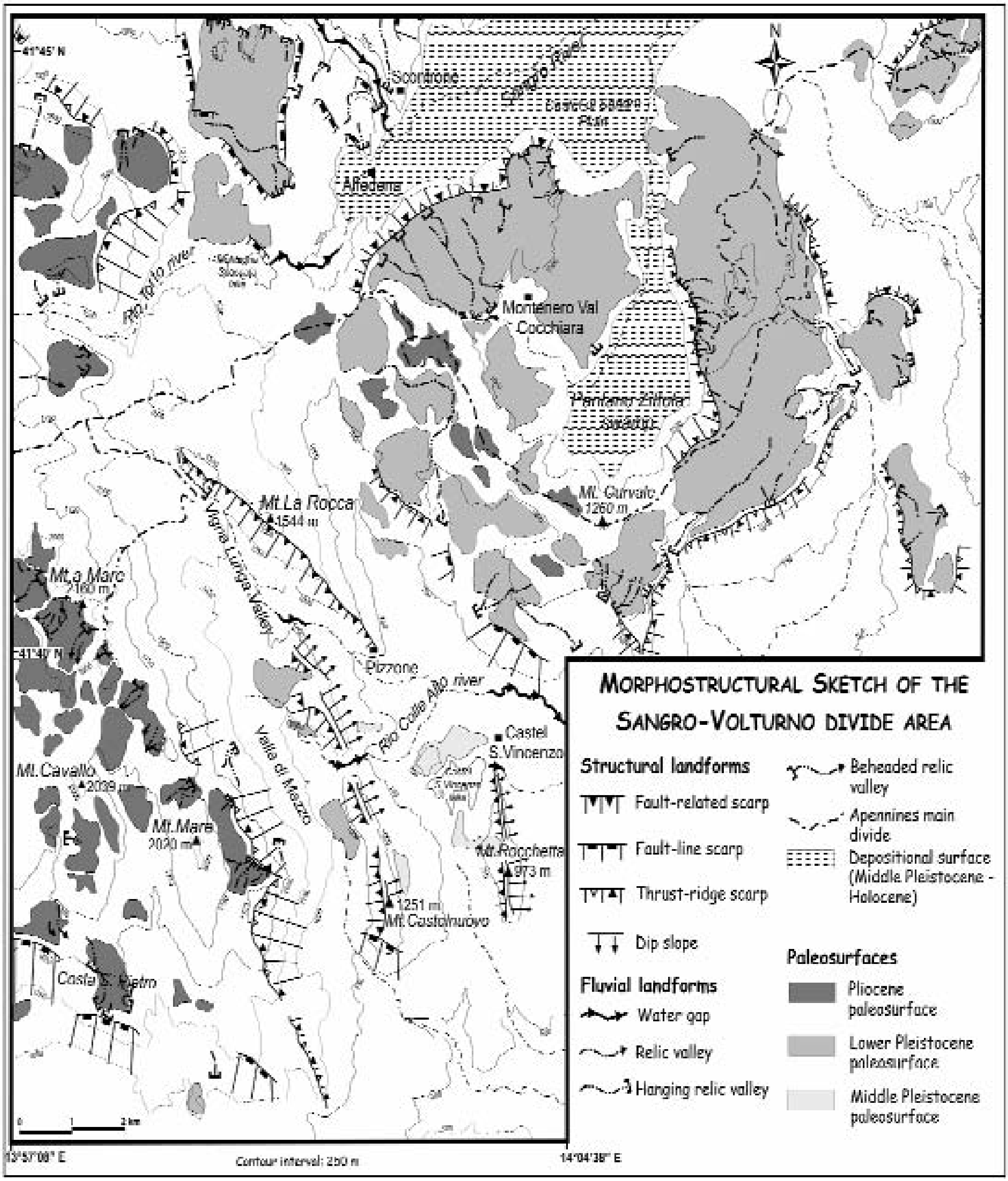


FIG. 5 - Morphostructural map of the Sangro-Volturno divide area.

range, one of the greatest orographic features in the whole Apennines chain. The massif appears as a huge prismatic body (figs. 3b, 4a) with a roughly tabular summit, gently sloping towards WSW, and bordered to the N, E and S by high escarpments. The topographic culmination of the Mainarde range roughly corresponds to the anticlinal axis, here exposing Cretaceous-Palaeogene carbonates, while in the SW and the NE flanks Jurassic-Cretaceous and Palaeogene-Miocene carbonates respectively crop out.

Several paleosurfaces are found up to 2000 m a.s.l. In some cases, W and SW of the main peaks alignment, they have a local structural control, due to the attitude of bedrock strata, especially in the most elevated areas (e.g.: Coste dell'Altare area, fig. 6). These paleosurfaces anyway preserve some elongated patches of a relic hydrographic network with low-gradient, beheaded trunks and wind gaps, generally flowing towards the S and SW (*e.g.*: between Mt. Cavallo and Mt. a Mare). In the Abruzzi interiors, a few kilometers N of the study area, several paleosurfaces at similar elevations (> 1600 m a.s.l.) are reported (Bosi & *alii*, 1996; Galadini & *alii*, 2003) and, according to those authors, their age is generically Pliocene. In fact, all the Lower-Middle Pleistocene continental deposits in this sector of the Apennines are hosted in valleys deeply entrenched in the highest paleosurfaces. Possibly, the highest Meta-Mainarde paleosurfaces were generated in proximity of the sea level, but their relic hydrographic network testifies for a more decisive sub-aerial moulding. The abrupt truncation of this ancient network is interpreted as a response to uplift of the Meta-Mainarde thrust sheet.

The escarpments bordering the massif are set up on thrust planes (northern and eastern slopes) and strike-slip faults (southern slope). They put the carbonates of the Meta-Mainarde thrust sheet in contact with the siliciclastics. The 11 km long eastern escarpment is N-S oriented, and its height varies from 300 m to over 1000 m. It has a polyphasic transversal shape, due to the presence of some planar paleosurfaces that cut through strata with variable dip (e.g.: La Ferruccia area, at 1750 m a.s.l.; fig. 7). The more than 11 km long southern escarpment has an E-W orientation. It also has a very variable height, with a maximum value of 1000 m. It possesses a polyphasic transversal shape, for the presence of paleosurfaces between 1400 m and 1600 m a.s.l. (e.g.: Costa S. Pietro area, fig. 5), where several hanging valleys can be observed.

A spectacular morphological signature of the massif relies on its set of glacial cirques and troughs. They originated during the cold stages of the Middle-Late Pleistocene (Cinque & *alii*, 1990; Jaurand, 1998; Giraudi, 2003; fig. 9). Two main groups of Late Pleistocene cirques can be distinguished at different heights: the first one at 1750-1900 m (Mt. Metuccia, Mt. a Mare, Coste dell'Altare, Mt. Mare), the second one at 1950-2100 m (Mt. Meta, Coste dell'Altare). The main glacial troughs (e.g.: Pagana Valley) are 4-6 km long, and extend up to 1600-1700 m a.s.l., showing a clear U-shaped cross section.

The Mt. S. Michele, Mt. La Rocca and Mt. della Rocchetta ridges

East of the Meta-Mainarde massif there are three narrow carbonatic ridges (the Mt. S. Michele, Mt. La Rocca and Mt. della Rocchetta). They show a very similar morphostructural setting.

The Mt. S. Michele ridge is N-S oriented and the beds dip almost constantly 60°-70° to the E. The western slope

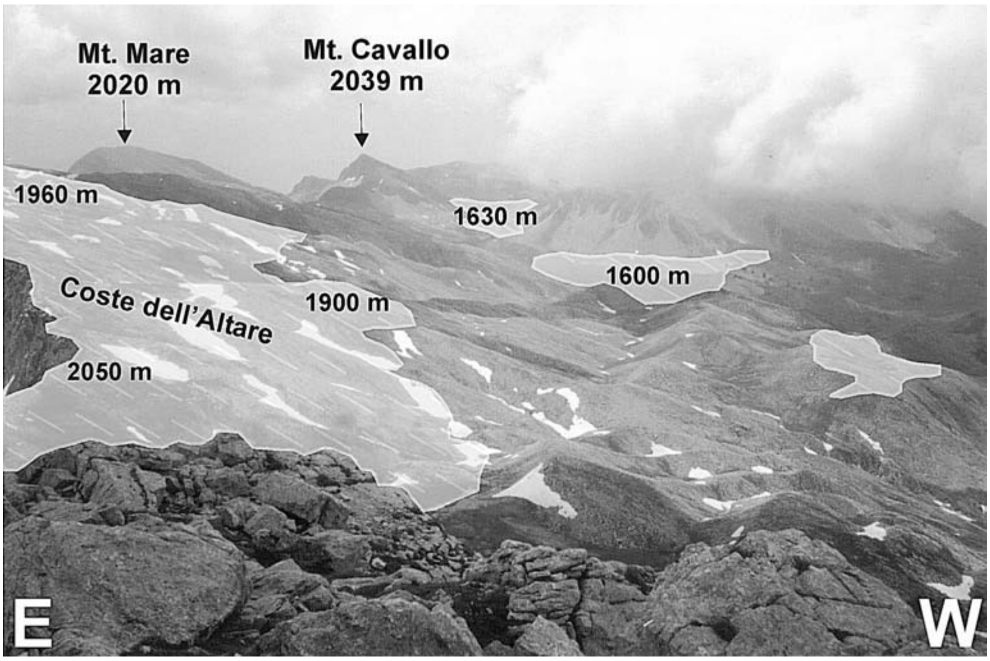
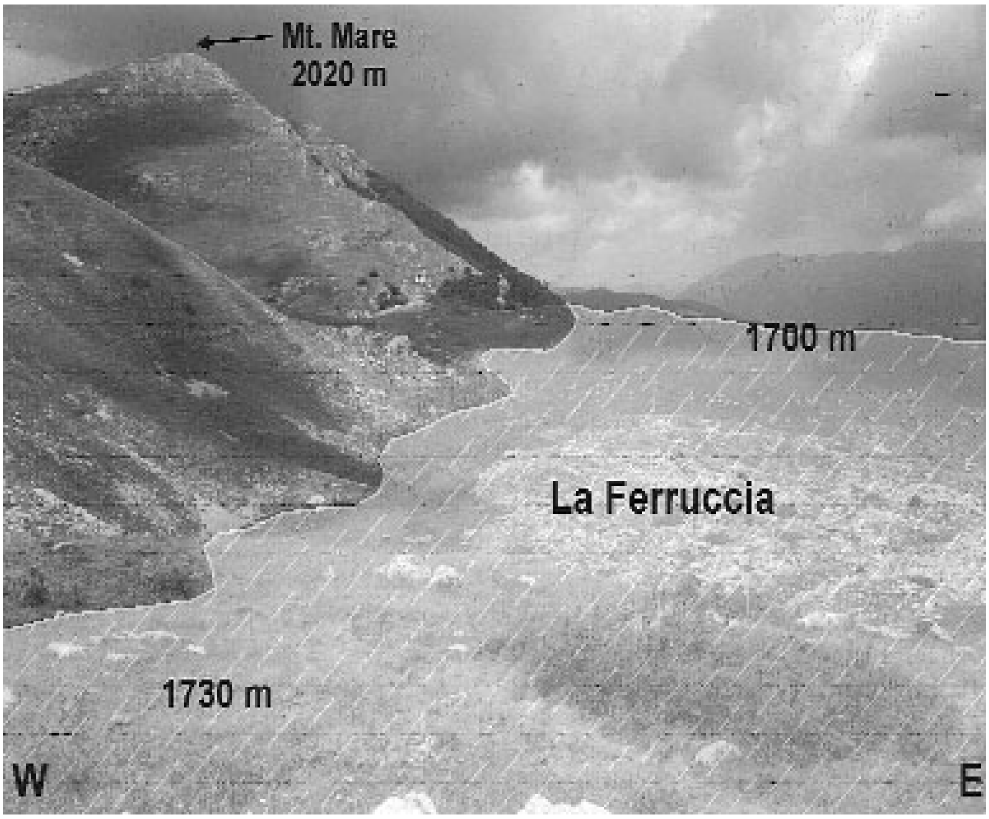


FIG. 6 - Paleosurfaces in the central-eastern portion of Meta-Mainarde massif (hatched, in transparency), around Coste dell'Altare area. View from Mt. Meta peak (2242 m), towards the S.

FIG. 7 - Paleosurface carved on limestones (hatched, in transparency), at La Ferruccia area, Meta-Mainarde massif. View from the S.



is a 6 km long fault-line scarp with variable height (ranging between 100 m and 400 m). It is transversally cut by the 300 m deep Rio Colle Alto water gap (fig. 5). The eastern dip-slope, partially covered by siliciclastics, also shows a slightly variable height with well preserved flat irons.

West of Mt. S. Michele, the Valle di Mezzo is a narrow structural corridor, hosting siliciclastics and a thin cover (a few meters) of coarse slope debris and reworked glacial deposits. The latter consist in rounded, carbonate cobbles and boulders, in a yellowish sandy matrix. In this valley some paleosurfaces at 900-1000 m a.s.l. are preserved (fig. 5). In particular, at Casone del Medico (1050 m a.s.l.), a small, flat paleosurface carved on siliciclastics and carbonates remoulds the western fault of the Mt. S. Michele and is clearly linked to a wind gap that cuts transversally the ridge.

The Mt. S. Michele and Mt. La Rocca ridges are separated by another very narrow valley (Vigna Valle Lunga), underlain by siliciclastics. The latter ridge has a NW-SE orientation and it is bordered to the SW by a more than 5 km long fault-line scarp. The height of this fault-line scarp increases from the NW (where it is few tens of meters) to the SE, with a maximum range of about 500 m. The cross profile of this slope shows a polyphasic shape, due to the presence of a very steep basal cliff, at some places higher than 100 m and about 3 km long (fig. 5). The thick slope debris cover at the piedmont shows no evidence of faulting. The north-eastern side of Mt. La Rocca is a dip-slope displaced by transversal faults, which isolate some hogbacks (fig. 5). Its height rapidly increases southeastwards, while it gradually disappear under the siliciclastics moving towards the Apennines main divide.

The 2.5 km long Mt. della Rocchetta ridge rises on a slightly undulated landscape carved on siliciclastics. The ridge is N-S oriented, with a fault-line scarp on the W side and an eastern dip-slope (the beds dip constantly 40° to the E). The western fault line-scarp has a very variable height (ranging from nearly zero, in correspondence of La Forcella paleosurface, up to 400 m; fig. 8). It shows a basal scarplet whose height irregularly ranges between 1 m and 15 m: it can be followed all along the western slope, with the exception of La Forcella area (at 800 m a.s.l.), where it disappears under the siliciclastics. At the base of the eastern dip-slope, the Rocchetta al Volturno travertine plate crops out. It covers a siliciclastic bedrock and forms two broad terraced depositional surfaces at 550 m and 500 m a.s.l., with an intervening progradational slope (Brancaccio & *alii*, 1988).

The Castel San Vincenzo area

The hilly area comprised between the Mt. S. Michele and Mt. della Rocchetta ridges is underlain by siliciclastics. It gently slopes towards the E. Very small paleosurfaces are present between 1000-700 m a.s.l. (fig. 5). Near Castel San Vincenzo town, two of these paleosurfaces are cov-

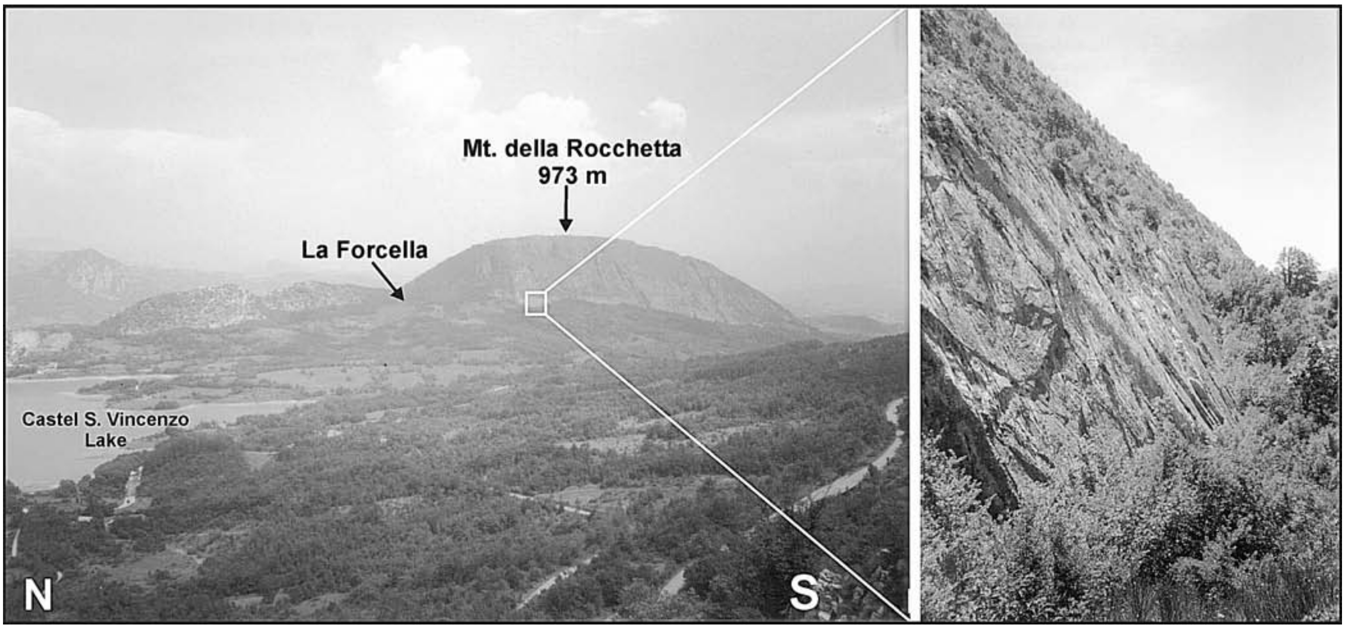


FIG. 8 - The western escarpment of Mt. della Rocchetta (view from the W). Note discontinuous basal scarplet and the variable height of mountain front, which almost disappears in the middle of the ridge (La Forcella area). On the right, the fault plane is shown where it reaches its maximum height (15 m).

ered by continental deposits. In the first case, the town itself is sited on a 40 m thick travertine plate, which stands over an erosional surface cutting siliciclastics. Nearby, a little paleosurface is covered by a thin (about 10 m) conglomerate deposit, whose top is at 754 m a.s.l. (fig. 2). This conglomerate in its basal portion shows a chaotic texture, and is composed of mainly carbonatic, arenaceous and subordinately cherty pebbles and cobbles, embedded in a clayey matrix. It grades upward into a massive clayey deposit. The basal conglomerate could be the a debris-flow, while the deposit as a whole can be related to a fluvial-lacustrine environment. The Castel San Vincenzo conglomerate, as the adjacent travertine, hangs more than 100 m over the present-day active thalwegs of the Volturno River basin.

WSW of Castel San Vincenzo, at 780 m a.s.l., we found another completely isolated conglomerate outcrop. This conglomerate is almost exclusively composed of Middle Miocene calcarenites, most probably fed by the eastern dip-slope of the neighbouring Mt. S. Michele ridge. It rests on the top of the Colle Salamuni hill, more than 150 m high over the next active thalweg.

The continental deposits in the Castel San Vincenzo area testify local ancient base-levels at least 100-150 m higher than today. This implies a subsequent radical reorganization of river network, with a noticeable amount of siliciclastics erosion. The remnants of this paleo-landscape are found in correspondence of the small paleosurfaces resting between the Mt. S. Michele and Mt. della Rocchetta ridges. The morphological position of the conglomerate outcrops is nowadays completely suspended. Therefore, they are certainly older than the Rocchetta al Volturno travertine, which grades into the recent Volturno alluvial plain and stands 200-250 m below the Castel San Vincenzo travertine. For this reason, these conglomerate outcrops can be tentatively ascribed to the late part of Middle Pleistocene. The aforementioned paleosurfaces are clearly older than the Castel San Vincenzo deposits and younger than the paleosurfaces standing around the Apennines divide area over 1000 m (see next). Therefore, a general Middle Pleistocene age for these landforms can be confidently hypothesized.

The Apennines divide area around Campitelli

North of Mt. La Rocca, an arch-shaped morphologic high near Campitelli depicts the present-day divide of the Sangro and Volturno rivers. Its average elevation decreases eastwards from about 1600 m to 1100 m a.s.l. The bedrock is made up of siliciclastics and sparse carbonate spurs. Between Campitelli and Valle Fiorita, wide outcrops of glacial deposits (fed by the neighbouring Meta-Mainarde massif) and associated moraines are present (Cinque & *alii*, 1990; Jaurand, 1998, fig. 9). The most recent ones have a very fresh morphology and the Authors related them to the Last Glacial Maximum (about 23-21 kyr BP: Giraudi, 2003). The Apennines main divide splits around the Valle Fiorita moraines (fig. 5), which now form an endorheic area hosting some lacustrine, Holocene deposits (Giraudi, 1997).

Just E of Campitelli area, two large outcrops of glacial deposits, more than 100 m thick, form the body of La Montagnola (1566 m) and Rocca Ranalda (1465 m) hills. These deposits consist of a chaotic mixture of carbonate boulders, with variable roundness, embedded in an abun-

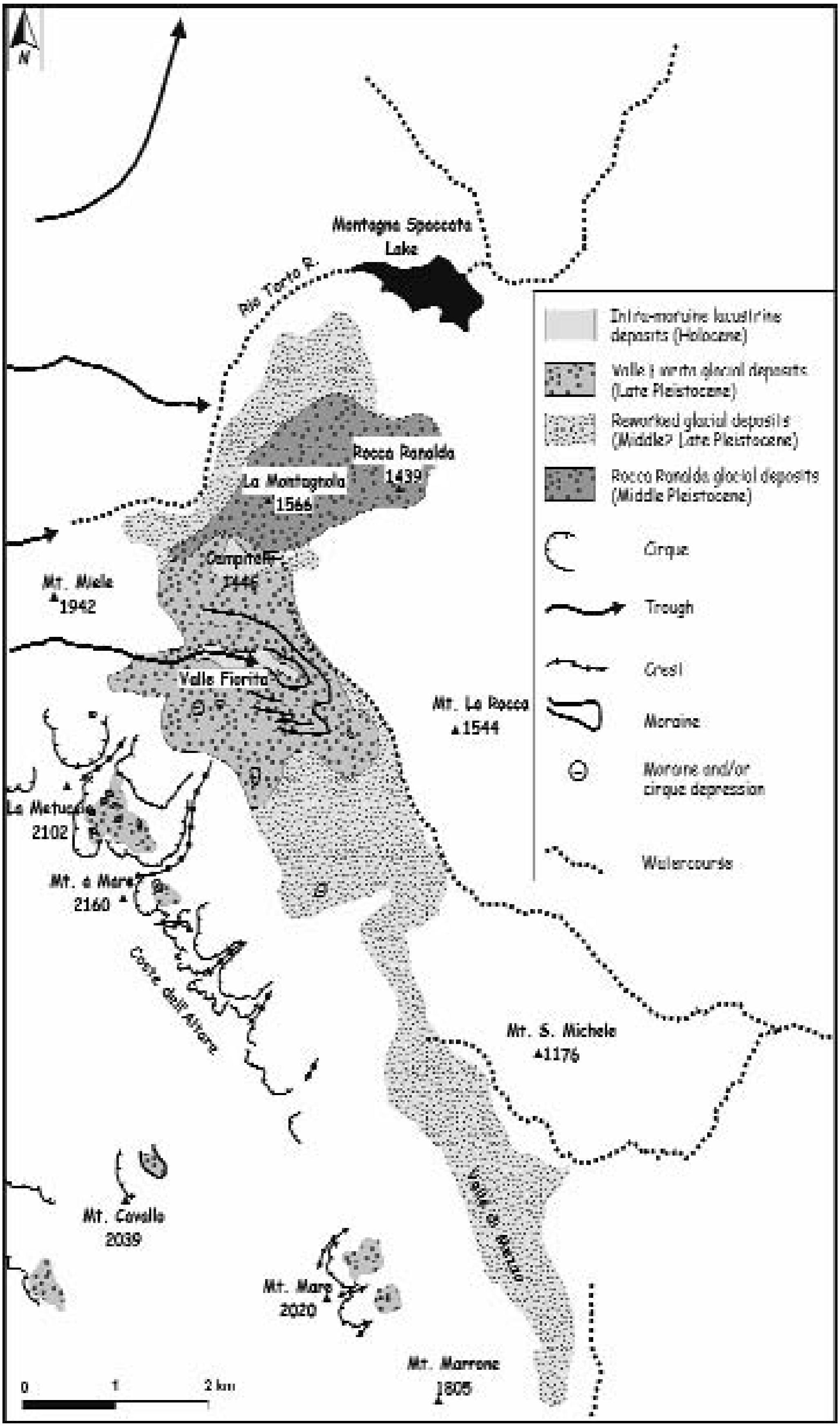


FIG. 9 - Simplified map of the main glacial deposits and landforms in the study area.

dant, yellowish, sandy-silty matrix. They form isolated topographic highs and clearly hang over the adjacent active thalwegs. They can be followed to the N until about 1250 m a.s.l. The age of these glacial deposits is unknown, anyway we hypothesize a late Middle Pleistocene age. In fact, these depositional landforms completely lost their original morphology, due to the strong incision they were subject (more than 150 m), while the Late Pleistocene landforms are still perfectly preserved. Moreover, these ancient deposits form isolated highs, and they hang over valleys hosting four orders of Late Pleistocene fluvial terraces (see next), so they are surely older than these terraces.

North of Campitelli, in the Adriatic flank of the study area, the Rio Torto Valley is incised in a narrow corridor between the north-eastern termination of the Meta-Mainarde massif and the southern termination of Mt. Greco ridge. Bedrock is made of siliciclastics, while in the final trunk the river cuts through Cretaceous-Miocene carbonates, giving rise to a more than 70 m deep gorge. In the left flank of the valley some small ridges, bordered by fault-line scarps on their W side and dip-slopes on their E side (generally exposing Miocene carbonates) are present (*e.g.*: the N-S trending Barrea fault-line scarp). The landscape is dominated by very wide paleosurfaces carved on pelitic-arenaceous turbidites, between 1200-1000 m (fig. 10). These paleosurfaces can be correlated with other paleosurfaces, cutting both carbonates and siliciclastics, in the left flank of the Sangro River gorge, at 1200-1300 m. Numerous, well preserved, beheaded and hanging fluvial-karstic valleys, sometimes with a sinuous channel pattern, can be observed NW of Alfedena and Scontrone towns (fig. 5).

All the aforementioned relics of paleo-landscape (both paleosurfaces and the paleovalleys inside) hang above the thalweg of the deep and narrow Sangro River gorge (WNW of Scontrone town, fig. 5), which stands 300-400 m below, between about 930 and 870 m a.s.l.. These paleosurfaces are a striking example of ancient base-levels completely isolated from present-day hydrographic network. The Sangro River gorge, due to its length (> 6 km), depth (even more than 400 m), sinuosity, and clear discordance with the structures it cuts (*e.g.*: the Barrea fault-line scarp), is superimposed. This means that the Sangro River originally flowed in a wide, low gradient valley whose remnants are represented by the paleosurfaces now resting at 1200-1000 m between Barrea and Alfedena («paleo-Sangro» valley: see the final section).

The Middle Pleistocene glacial deposits of La Montagnola and Rocca Ranalda partially stand over the middle Rio Torto Valley paleosurfaces, that surely pre-date this depositional event (see next).

The Montenero Val Cocchiara area

The Montenero Val Cocchiara klippe is a broad open syncline, with beds generally dipping gently towards the N. This klippe forms a horse-toe shaped thrust-ridge. Eocene-Miocene limestones crop out on the main topographic culminations, particularly in the western and northeastern portions of the klippe, where the thin (some meters) siliciclastics cover is at places still preserved (that is, several hundreds meters of siliciclastics are nowadays missing). In the central part of the area, the Pantano Zìttola (fig. 5) is a 4 km long flat-bottomed polje, NNE-SSW oriented. It is not bounded by any high angle fault, and its origin seems clearly related to the outcropping impermeable siliciclastics, in the footwall of the klippe basal thrust.

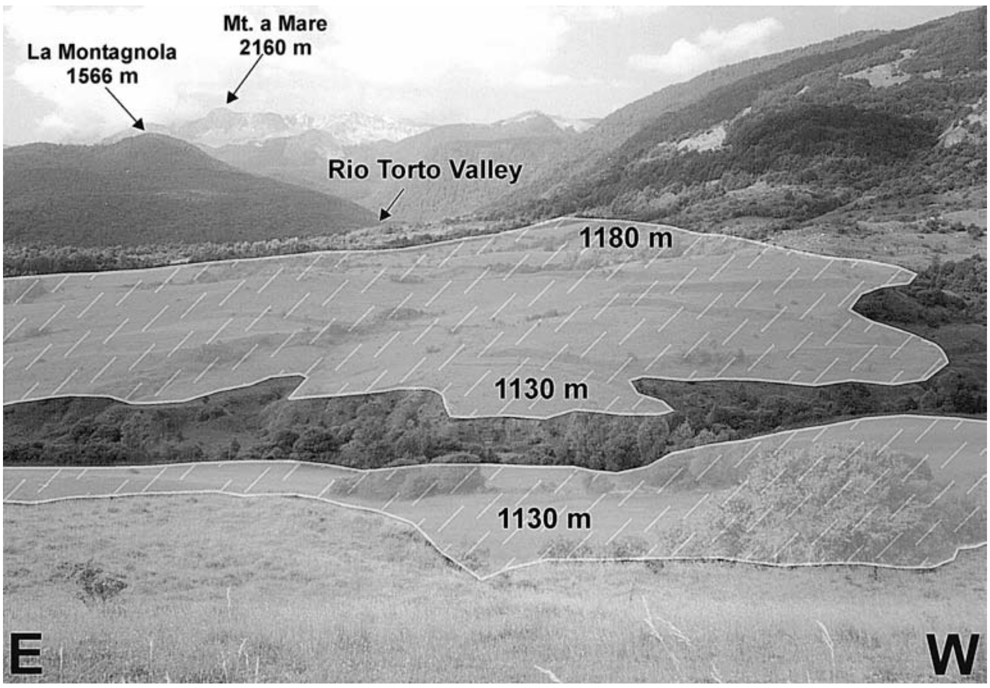


FIG. 10 - Wide paleosurface (hatched, in transparency) carved on siliciclastic bedrock in the left flak of the Rio Torto Valley, at about 1100 m a.s.l. View towards the S. On the background, La Montagnola hill (made of hanging, Middle Pleistocene glacial deposits) and the Meta-Mainarde massif.

This klippe hosts the widest paleosurfaces in the study area (fig. 5), and they now stand between 900 m and over 1100 m a.s.l. The average elevation of these paleosurfaces in the western portion of the klippe is quite similar to the ones preserved in the middle Rio Torto Valley. Moreover, several beheaded, sinuous, relic valleys, flowing with very low gradient from NW to SE in this portion of the klippe, suggest the possible ancient continuity of all these patches of paleo-landscape.

The Castel di Sangro Plain

The Sangro River Valley widens after the junction with the Rio Torto River, giving rise to an alluvial plain about 2 km wide and more than 5 km long, between about 870 m and 830 m a.s.l. (Castel di Sangro Plain). The alluvial deposits are about 20 m thick (Capelli & *alii*, 1998). Four terraces have been recognized, in both the valley flanks. The highest terrace, near Villa Scontrone town, in the left flank of the valley, stands about 50 m over the thalweg, at 920-915 m a.s.l.. It is represented by some erosional surfaces carved on siliciclastics, hosting small patches of carbonate gravels. The second terrace, carved on both the flanks of the valley, stands at 900 m a.s.l. It is part of the depositional surface on which Alfedena was built. It is made of calcareous pebbles fed by both Rio Torto and Sangro rivers. Immediately below, the third depositional terrace stands on both the flanks of the valley, between 870 m and 850 m a.s.l., in clear continuity with the bottom of Pantano Zìttola. The fourth, Holocene terrace is depositional, and it stands 1-2 m above the present-day thalweg.

There is more than 300 m of relief between these Late Pleistocene-Holocene Castel di Sangro Plain terraces and the paleosurfaces suspended by the Sangro River gorge between Barrea and Alfedena.

Some other paleosurfaces, underlain by siliciclastics and gently sloping to the W, can be found in the right flank of Castel di Sangro Plain, from 870 m up to over 1000 m a.s.l.

General remarks on morphostructural setting of the study area

At the end of this section, some general remarks, useful for the next discussion and interpretation, can be briefly pointed out.

As regards morphostructures, it was observed that: 1) all the slopes bordering the main topographic highs put in contact carbonates and siliciclastics; 2) the elevation of the carbonates-siliciclastics limit along each slope is extremely variable, lowering towards the ridge edges; 3) the few, apparently *fresh* basal scarplets (*e.g.*: Mt. della Rocchetta western slope; Barrea fault), have a very discontinuous expression which disappears at the ridge edges, *i.e.* where the fault trace crosses the only siliciclastics; 4) no Quaternary depocenter relatable to faulting-induced damming was found; 5) no tectonic displacement of recent continental deposits (both glacial deposits, talus scree or others) was found.

As regards paleosurfaces, it was observed that: 1) several paleosurfaces are preserved all over the study area, in the 2100-750 m elevation range, carved both on carbonates and siliciclastics; 2) they generally appear reciprocally nested, with no clear evident displacements by means of high-angle faults (*i.e.* no evident tectonic duplication of paleosurfaces was found); 3) some paleosurfaces seal the lateral prosecution of fault-bounded slopes (*e.g.*: Casone del Medico and La Forcella sites); 4) the paleosurfaces standing over 1600 m are most probably Pliocene in age, and this is surely true for the highest ones on the Meta-Mainarde massif, which could have been generated in proximity of the sea level; 5) the paleosurfaces standing at 1200-1000 m are the widest and best preserved in the study area, are most probably Lower Pleistocene in age and are deeply incised (300-400 m); 6) the paleosurfaces standing between around 800-750 m are Middle Pleistocene in age and are locally deeply incised (150-200 m).

As regards the hydrographic network and incision phenomena, it was observed that: 1) some diaclinal water gaps (*e.g.*: the Rio Colle Alto and Sangro River gorges, the latter having a sinuous path) are superimposed across the morphostructural highs; 2) the elevation of siliciclastic cover on fault-related and fault-line scarps drastically lowers in correspondence of these diaclinal water gaps; 3) the late Middle Pleistocene continental deposits (both in the Adriatic and in the Tyrrhenian flank of the study area) were incised for at least 100-150 m; 4) the highest fluvial terrace in the Castel di Sangro Plain (Late Pleistocene in age) stands 50 m over the present-day thalweg and more than 300 m below the paleosurfaces at 1200-1000 m in the middle Sangro River valley.

DISCUSSION AND CONCLUSIONS

The roles of erosion and tectonics

The main results of our analyses can be summarized in few basic points. The morphostructural setting of the study area seems to be dominated by structure-controlled landforms (e.g.: Ascione & Cinque, 1999), or *morphosculptures* (see D'Alessandro & *alii*, 2003 for a comprehensive discussion). According to the scheme proposed by D'Alessandro & *alii* (2003), we grouped the main morphostructural features in some simple categories. They relate each main structural landform to its tectonic and geomorphological setting (as described in the previous section; figs. 1a, 1b, 5). We namely distinguished among: *faulted homocline ridges*, *i.e.* ridges bordered by a fault-related/fault-line scarp and a dip-slope on their sides (*e.g.*: the Mt. S. Michele, Mt. la Rocca, Mt. della Rocchetta ridges); *exhumed thrust ridges*, *i.e.* thrust-related spurs exhumed by a previous erodible cover and bordered by fault-line scarps and thrust-related scarps (*e.g.*: the Montenero Val Cocchiara klippe); *exhumed anticlinal ridges*, which are a variation of the previous category, when the exhumed structure is a fault-related fold, bounded by fault-line/fault-related scarps (*e.g.*: the Meta-Mainarde massif). All of them are landforms with a passive structural control, owing their expression mainly to differential erosion phenomena. Differential erosion was enhanced by the occurrence of two main bedrock types, *i.e.* carbonates and the often unconsolidated, largely clayey siliciclastics, with a strikingly different erodibility.

There are only few available data to quantify the relative *hardness* of carbonates and *softness* of siliciclastics, either in general (see, for example: Saunders & Young, 1983; Osborn & *alii*, 2006) or particularly in the case of the long-term geological history of the Apennines. Studies on exhumation of Apennines Tertiary siliciclastics (strongly dependent on the analytical methodology and the assumptions made about past geothermal gradients) give robust evidence that these rocks are subject to high exhumation rates, which can be confidently converted to erosion estimates. Bartolini & *alii* (2003) summarize a long list of works regarding the exhumation of Northern Apennines rocks: average exhumation rates > 1.5 mm/yr in the last 2 Myr, affecting since their surface exposure Miocene sandstones (now outcropping on the Apennines divide) imply strong erosion since the Late Pliocene. As regards the Central Apennines, Calamita & *alii* (2004) calculated 2500-3000 m of exhumation in the last 4-5 Myr for several samples of Miocene-Pliocene foredeep sandstones and clays, now outcropping in some deep depressions, between the Marsica and Gran Sasso ranges.

Geomorphological evidences collected in the Central-Southern Apennines in the last years (*e.g.*: Brancaccio & Cinque, 1988; Ascione & Cinque, 1999) testify, in this temperate climatic settings, for differential erosion promoted by the juxtaposition of carbonates and siliciclastics, suggesting very low rates of carbonates downcutting and downwearing (mainly due to karstic dissolution) compared to those affecting the siliciclastics. However, the landscape of the region gives the most striking evidence of the different erodibility of these rock types: topographic highs are carved in carbonates, they often preserve large summit interfluves bounded by steep slopes and are cut by deep and narrow water gaps; the adjacent topographic lows are underlain by siliciclastics, with wide valleys and gentle slopes subject to widespread landsliding.

Besides the aforementioned features, our study area offers further evidence of the different erodibility of these bedrock types. In fact, with the exception of the Meta-Mainarde massif, where the summit areas (at 2000-2200 m a.s.l.) expose Cretaceous-Paleogene limestones (and only at the northern rim of the anticline, below 1600 m a.s.l., Miocene limestones crop out), the carbonates downwearing affecting all the other thrust sheets is negligible, presumably no more than some *tens* of meters: the top of Miocene carbonates is well preserved on the Mt. Greco, Mt. la Rocca, Mt. S. Michele, Mt. della Rocchetta and Montenero Val Cocchiara units. On the other hand, huge volumes of siliciclastics were eroded everywhere: the Mt. Greco, Montenero Val Cocchiara and Mt. La Rocca units were stripped of several *hundreds* meters of Late Miocene - Lower Pliocene clay and sandstone. Since the genesis of the oldest paleosurfaces, particularly those cutting carbonates, a certain degree of karstic and sub-aerial reworking is likely. Anyway their overall erosion is negligible if compared with the subsequent lowering of the adjacent valleys carved on siliciclastics. Therefore, paleosurfaces can be confidently considered a tool for estimating long-term surface uplift.

In our study area, the occurrence of paleosurfaces from summit areas to progressively lower elevations (which, at some places, give rise to polyphasic slopes, *e.g.*: the eastern and southern slopes of the Meta-Mainarde massif) appears as the response to a stepped erosional lowering of the topographic surface. Such a scenario does not completely rule out important tectonic displacements of the topographic surface in this sector of the Apennines. The separation of local tectonics ad erosion in the genesis of relief along each fault-related slope is however a very difficult task. The cross-cut relationships between fault-related/thrust-related scarps and paleosurfaces can offer a solution (fig. 12). We discuss them in the followings.

The contribution of erosion in the genesis of relief around the Meta-Mainarde massif is mainly suggested by the very variable height of its eastern and southern escarpments. These more than 1000 m high slopes could be the result of an exclusively thrusting-related uplift or, conversely, they could have been generated by a progressive dismantling of the siliciclastics ahead of the thrust ramp. Maybe a combination of the two processes can better explain the complex relief genesis and the polyphasic shape of these slopes. The gentle tilting to the SW of the highest (1900-2100 m) paleosurfaces might have resulted from earlier thrust activity (in this case, the highest paleosurfaces should pre-date or be coeval to thrusting). It appears clear, anyway, that most of relief of this massif was already accrued when a low relief landscape, now resting as paleosurfaces at 1200-1000 m (between the high Rio Torto Valley and the Valle di Mezzo), was forming. This means that, during the Lower Pleistocene, the Meta-Mainarde massif had already gained no less than a thousand meters of relief over the adjacent «paleo-Sangro» valley.

In the case of the Mt. S. Michele and Mt. della Rocchetta ridges, the two small paleosurfaces at Casone del Medico (at 1050 m) and at La Forcella (at 800 m) clearly seal the fault displacements on their western flanks, presumably between Lower and Middle Pleistocene times (fig. 12). In both cases, these paleosurfaces stand about 200 m over the next active thalweg and about 150-200 m under the ridge crests. The relative elevation of the paleosurfaces over the thalweg is indicative of the amount of downcutting occurred since their moulding. The relative elevation of the crests over the paleosurfaces can be due to tectonic displacement and/or differential erosion. The clear separation of tectonics and erosion is very difficult, anyway Pleistocene morphological offsets along these faults are on the order of about 200 m.

With the exception of the Mt. La Rocca structure, whose southwestern fault-related scarp suggests possible tectonic activity also during Middle Pleistocene times, the study area lacks any clear stratigraphical and morphostructural evidence of Middle-Late Pleistocene local tectonic activity.

The long-term geomorphological evolution

We outline a possible scheme of the long-term geomorphological evolution of this sector of the Apennines, with particular attention to the relief genesis and surface uplift (fig. 11). In this scheme, some elements play a major role, such as local tectonic uplift coeval with thrust-belt accretion, large-scale uplift and differential erosion.

As regards the Meta-Mainarde massif, probably since the Lower Pliocene the summit paleosurfaces were uplifted by means of thrusting (fig. 12). This uplift was likely discontinuous in time. In fact, other low relief surfaces on the eastern and southern escarpments of the massif, now resting at 1750-1400 m, were moulded. At the end of the Pliocene, the Meta-Mainarde massif had reached no less than one thousand meters of elevation over the adjacent areas to the E. In these areas several hundreds meters of siliciclastics had already been eroded, giving rise to a substantially gently rolling landscape. Probably, only at some places (top of Mt. La Rocca and Mt. S. Michele ridges; some isolated tops of the Montenero Val Cocchiara klippe and the southern termination of Mt. Greco ridge) exhumation of the carbonates had initiated. During this period, a transversal drainage established in the area between Meta-Mainarde massif and the Mt. S. Michele ridge.

Afterwards, probably in the early Lower Pleistocene, extensional faulting along the W border of Mt. S. Michele ridge and the SW border of Mt. La Rocca ridge took place. This faulting generated the narrow Valle di Mezzo. It also promoted a change in the hydrographic network, by means of captures that forced the flow to align parallel to the faults bounding the depression. Only the Rio Colle Alto water gap kept on downcutting the Mt. S. Michele ridge. Activity of the western fault of the Mt. S. Michele ridge occurred not later than Lower Pleistocene, as this fault is sealed by the paleosurface at Casone del Medico.

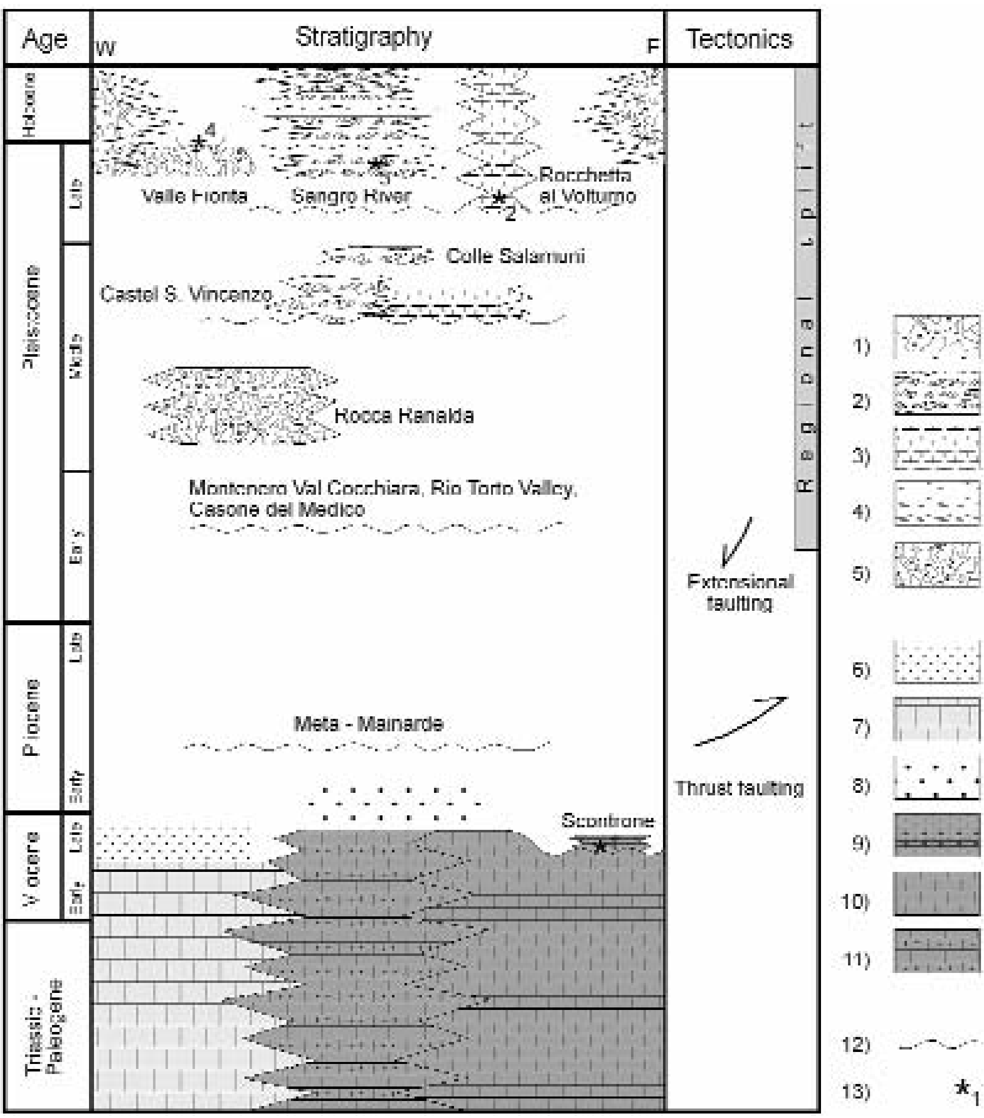


FIG. 11 - Synoptic scheme of the Mesozoic-Quaternary stratigraphy and Pliocene-Pleistocene tectonic and morphogenetic phases in the study area. Continental deposits: 1) slope deposits; 2) conglomerates; 3) travertine; 4) lacustrine deposits; 5) moraine. Marine deposits: Latium-Abruzzi unit; 6) siliciclastic deposits (Latium-Abruzzi unit); 7) by-pass margin carbonates. Apulia unit; 8) siliciclastic deposits; 9) detritic marls of Scontrone; 10) shelf carbonates; 11) slope to basin carbonates; 12) Paleosurface; 13) absolute age (1, Patacca & *alii*, 2006; 2, Brancaccio & *alii*, 1988; 3, Capelli & *alii*, 1998; 4, Giraudi, 1997). Time axis not in scale.

During the Lower Pleistocene, in the northern and eastern portions of the study area, the moulding of a wide, gently rolling erosional landscape took place. The «paleo-Sangro» valley was outlined between the Meta-Mainarde and the Mt. Greco massifs. The subsequent incision of the aforementioned landscape gave rise to the widest paleosurfaces in the study area, now resting between 1200-1000 m between the Rio Torto Valley and the Montenero Val Cocchiara klippe (fig. 12).

During the Middle Pleistocene, the present-day physiography of the study area started to be outlined. In this period, the vertical offset along the Mt. della Rocchetta western fault had already been attained (it is sealed by the La Forcella paleosurface). Moreover, at that time a phase of strong incision forced the reorganization of the river network, with the genesis of the spectacular Sangro River gorge between Barrea and Alfedena. Drainage network deepening strongly enhanced the local relief by means of differential erosion. This deepening, *after* the Middle Pleistocene, can be quantified in no less than 150-200 m, basing on the morphological position of the hanging continental deposits of the Castel San Vincenzo, La Montagnola and Rocca Ranalda areas, and the fluvial terraces in the Castel di Sangro Plain. It may be related to a lowering of the regional base-level, due to a relative uplift of the axial portion of the chain. The morphostructural cross-section (fig. 12) synthesize the most elements present in the study area (also by projecting them), showing the relative position of morphostructural elements and paleosurfaces together with the height distribution of the latter in order to clearify the cross-cut relationships considered for the timing of the morphostructural evolution of this Apennines chain sector.

It is important to note that, since the Middle Pleistocene, the Adriatic coastline gradually shifted eastwards for several kilometers in this sector of the chain, due to regional emersion and tilting of the Central-Southern Apennines foredeep. This shift would have lengthened the river courses, so that it is quite hard to explain the erosion of Lower Pleistocene paleosurfaces and the genesis of the Sangro River gorge as a result of regressive erosion (Ascione & *alii*, in press). The superimposed path of the Sangro River gorge suggests that incision was enhanced directly along the chain axis.

The minimum value of Quaternary *surface uplift* in the study area can be tentatively estimated basing on the amount of incision affecting the aforementioned Lower Pleistocene paleosurfaces. Unfortunately, the absolute elevation of their original base-level is unknown and probably impossible to determine. Therefore, the quantification of the surface uplift affecting this area since Lower Pleistocene times – some 400-500 m – is still speculative and our estimate surely stands for a minimum value. Nonetheless, the indubitable continental morphogenesis of the Lower Pleistocene paleosurfaces implies that cumulative Quaternary surface uplift in this sector of the Apennines was certainly lower than 1000 m. Furthermore, the timing of this uplift in the chain axis is not well constrained, because the hydrographic network incision could even be a far-field, delayed response to a regional relative base-level fall of much older age.

Indeed, the reconstruction of the long-term geomorphological evolution of the study area suggests that most of the absolute elevation in this portion of the chain was accrued during the Pliocene, particularly in correspondence of the Meta-Mainarde massif. This was done by means of thrusting. The uplift of the Pliocene paleosurfaces stands for a minimum value of the related absolute, large-scale, surface uplift of this portion of the chain during the Pliocene.

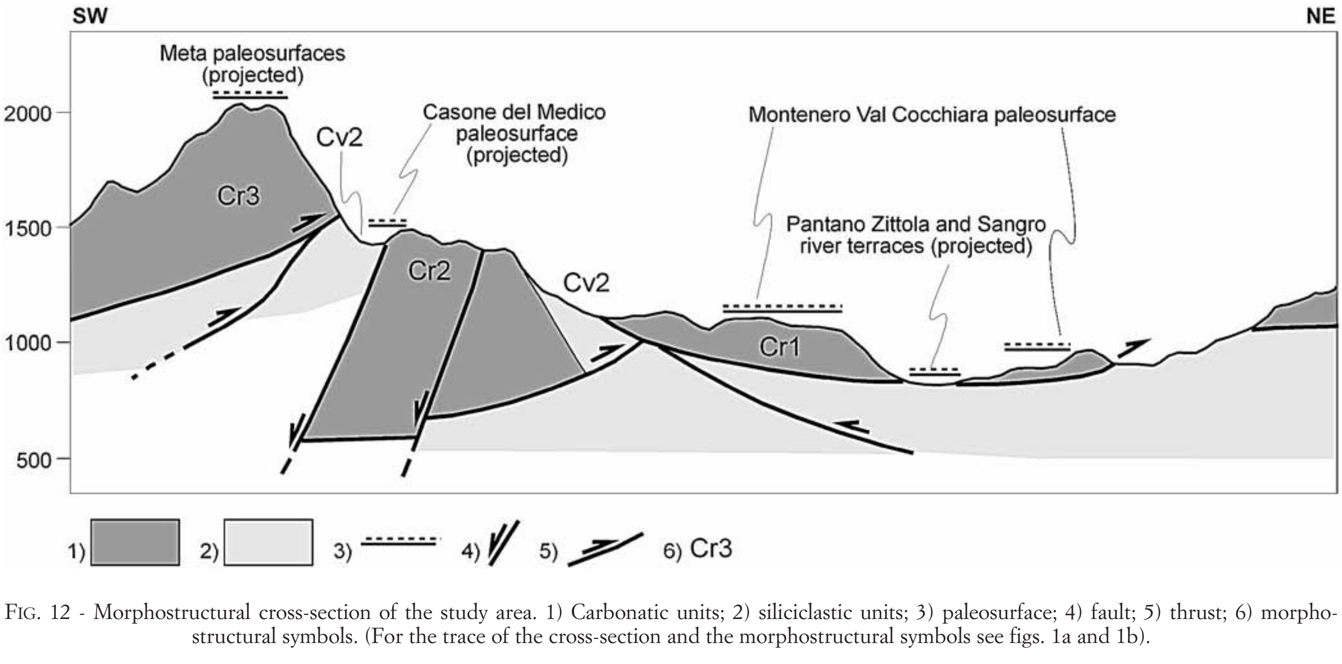


FIG. 12 - Morphostructural cross-section of the study area. 1) Carbonatic units; 2) siliciclastic units; 3) paleosurface; 4) fault; 5) thrust; 6) morphostructural symbols. (For the trace of the cross-section and the morphostructural symbols see figs. 1a and 1b).

The cessation of the main vertical tectonic displacements in the study area is testified by the moulding of the Lower Pleistocene paleo-landscape. Thereinafter, most of present-day relief was built by the erosional deepening of the main valleys and the subsequent hydrographic network reorganization, as a response to large-scale uplift. The value of this Pleistocene uplift is still unconstrained, but, basing on the amount of incision of the Lower Pleistocene paleosurfaces, it could be at least about 400-500 m.

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(Ms. received 30 May 2006; accepted 15 January 2007)