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Long- to short-term denudation rates in the southern Apennines: geomorphological markers and chronological constraints

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Abstract: Age constraints of geomorphological markers and consequent estimates of long- to short-term denudation rates from southern Italy are given here. Geomorphic analysis of the valley of the Tanagro River combined with apatite fission track data and radiometric dating provided useful information on the ages and evolution of some significant morphotectonic markers such as regional planated landscapes, erosional land surfaces and fluvial terraces. Reconstruction of paleotopography and estimation of the eroded volumes were perfomed starting from the plano-altimetric distribution of several orders of erosional land surfaces surveyed in the study area. Additional data about denudation rates related to the recent and/or active geomorphological system have been obtained by estimating the amount of suspended sediment yield at the outlet of some catchments using empirical relationships based on the hierarchical arrangement of the drainage network. Denudation rates obtained through these methods have been compared with the sedimentation rates calculated for two adjacent basins (the Pantano di San Gregorio and the Vallo di Diano), on the basis of published tephrochronological constraints. These rates have also been compared with those calculated for the historical sediment accumulation in a small catchment located to the north of the study area, with long-term exhumation data from thermochronometry, and with uplift rates from the study area. Long- and short-term denudation rates are included between 0.1 and 0.2 mm/yr, in good agreement with regional data and long-term sedimentation rates from the Vallo di Diano and the Pantano di San Gregorio Magno basins. On the other hand, higher values of exhumation rates from thermochronometry suggest the existence of past erosional processes faster than the recent and present-day exogenic dismantling. Finally, the comparison between uplift and denudation rates indicates that the fluvial erosion did not match the tectonic uplift during the Quaternary in this sector of the chain. The axial zone of the southern Apennines should therefore be regarded as a landscape in conditions of geomorphological disequilibrium.

Key words: southern Italy, landscape evolution, morphotectonics, drainage network, denudation rates.

Introduction

The estimation of uplift and denudation rates represents an active research field in studying the interaction between climate, tectonics and landscape evolution (Whipple et al. 1999; Bonnet & Crave 2003; Burbank et al. 2003; Whipple 2009). In tectonically active areas, a precise definition of such rates can offer important information about the landscape evolution and the interplay between uplift and denudation (Willett 1999; Willett & Brandon 2002; Wobus et al. 2003; Schiattarella et al. 2006; Bishop 2007; Pérez-Peña et al. 2009; Martino et al. 2009). In the last decade, estimation of erosion from *in situ* cosmogenic nuclide measurement permitted clarification of the roles of tectonics and climate in the evolution of mountain belts (Kirchner et al. 2001; Cyr & Granger 2008). Apart from cosmogenic data, paleosurfaces and, more generally, relict erosional land surfaces, strath terraces, and hanging slope deposits, represent the main geomorphological markers adopted in orogenic areas for the calculation of uplift and denudation rates (Widdowson 1997; Schiattarella et al. 2003, 2006; Bonow et al. 2006). For this reason, a fine age definition of such markers is needed for a more reliable estimation of the rates of both endogenic and surface processes. Tectonic- and climatically-induced processes were responsible for the base level lowering that led to fluvial incision and geomorphological "*de-activation*" of ancient landscapes. The term "de-activation" is here used to indicate a geomorphological stage in which uplift-related incision and tectonic fragmentation prevailed over erosional processes able to generate low-relief landscape (i.e. planation, slope decline). Tectonic uplift suspended the ancient erosional base level to which this gentle paleo-landscape was related, triggering a new morphogenetic stage, frequently characterized by morphogenetic conditions different from the previous ones. Thus, after the de-activation, geomorphological processes acting on the hanging land surfaces are strongly reduced.

Paleotopographic reconstruction of former base level morphology and comparison with the present-day topography can be used for a good estimation of the eroded volumes. In this work, both age constraints of morphological markers and long- to short-term denudation rates are furnished, based on the study of the lower valley of the Tanagro River in the southern Italian Apennines (Fig. 1). Besides the remarks on the relative age of the morphotectonic markers based on the

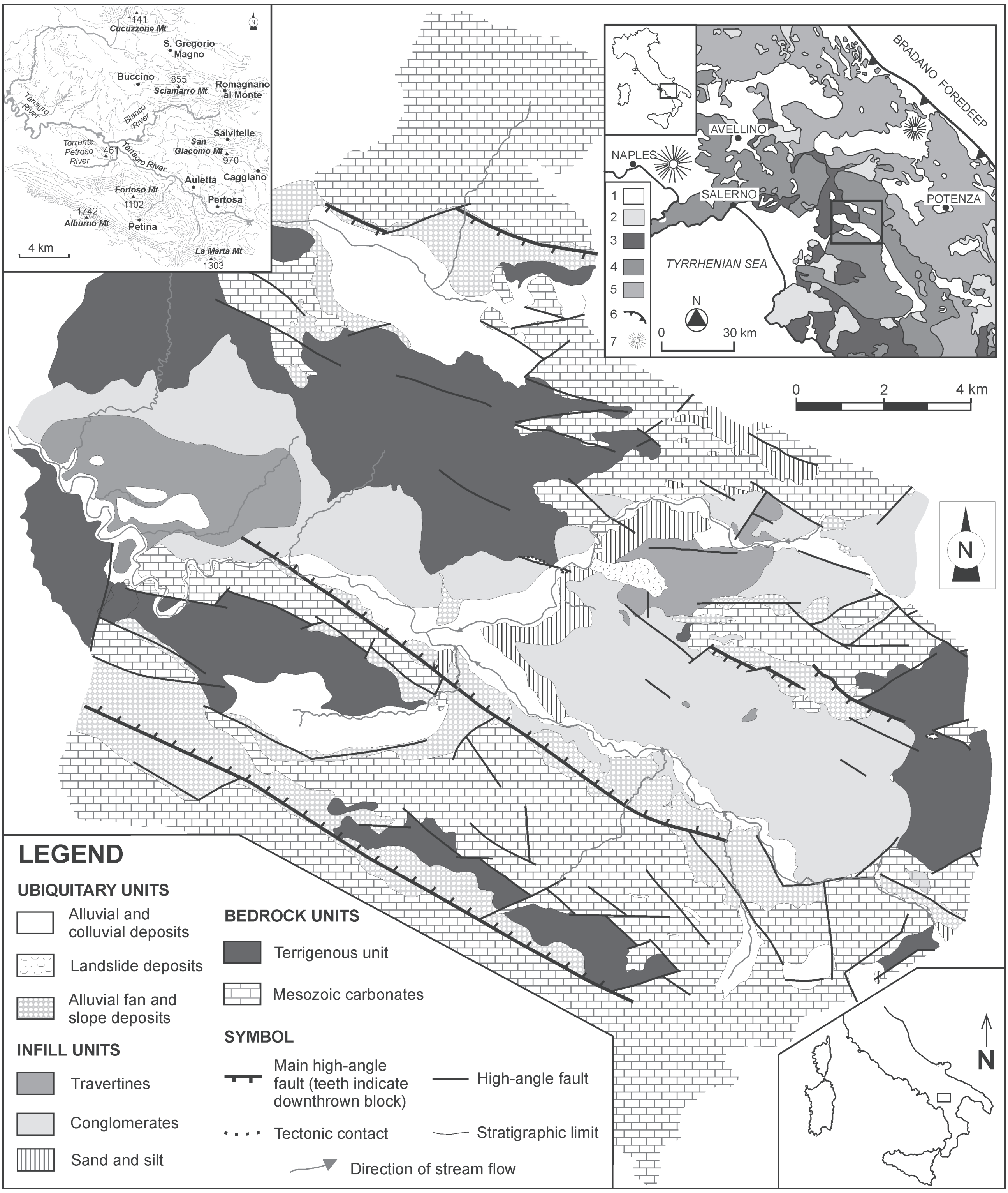


Fig. 1. Lithological sketch map of the study area. High-angle faults generally show a poly-modal distribution of kinematic indicators, with superimposition of left-lateral transtensional and dip-slip kinematics. In the frames: main toponyms (left), geological scheme of the southern Apennines (top) and location of the study area in the Italian peninsula (bottom). Legend of the geological scheme of the southern Apennines: **1** — Pliocene to Quaternary clastic deposits and volcanic products; **2** — Miocene syntectonic deposits; **3** — Cretaceous to Oligocene ophiolite-bearing internal units; **4** — Mesozoic-Cenozoic shallow-water carbonates of the Apennine platform; **5** — Lower-Middle Triassic to Miocene shallow-water and deep-sea successions of the Lagonegro-type; **6** — Volcanoes; **7** — Thrust front of the chain.

morphostratigraphic relationships with Pliocene and Quaternary deposits and with other geomorphological and tectonic features, new constraints have been obtained by the re-interpretation of apatite fission track data (Aldega et al. 2005; Mazzoli et al. 2008), whereas erosion rates have been calculated on the grounds of both missing rock volumes and morphometrically based estimation of suspended sediment yield. Finally, we performed a comparison of denudation rates at different spatial and temporal scales.

Geological and geomorphological setting

The southern Apennines (Fig. 1) are a north-east verging fold and thrust belt derived from the deformation of the African paleomargin (Cello & Mazzoli 1999, and references therein). Apart from the inner units (Sicilide Unit and Liguride Complex, *sensu* Bonardi et al. 1988) that crop out at the top of the thrust belt, this part of the Apennine chain is mainly composed of both shallow and deep water sedimentary units derived from the Mesozoic-Cenozoic circum-Tethyan domains and from the Neogene–Pleistocene foredeep deposits (Pescatore et al. 1999, and references therein). From Langhian–Tortonian times, the thrust front moved progressively toward the east (Malinverno & Ryan 1986), as is also documented by the age of syntectonic deposits (Pescatore et al. 1999). Thrusting in the frontal sector of the chain was followed by back-arc extension, responsible for the opening of the Tyrrhenian Sea (Pescatore et al. 1999). The original contractional structure was dismembered, during Late Pliocene–Pleistocene times, by strike-slip and extensional faults (Schiattarella 1998). As a consequence, this sector of the chain is morphologically articulated by the presence of longitudinal and transversal fault-bounded basins (Cinque et al. 1993; Schiattarella 1998). The main orientations of the strike-slip and extensional faults of the chain are N120° ± 10°, N150° ± 10° and N50° ± 20° trends. The Campania-Lucania Apennines are characterized by an asymmetric topographic profile. Indeed, the western slope of the chain has a greater mean gradient and a lower length than the eastern slope (Amato & Cinque 1999). The line of the highest elevations of the chain is markedly shifted toward the eastern slope and does not correspond to the regional water divide (Amato et al. 1995). Based on geological and geomorphological features (Cinque et al. 1993), the Campania-Lucania Apennines can be roughly subdivided into three parallel zones according to its long-axis (inner or Tyrrhenian zone, axial zone, and frontal or outer zone).

The axial zone is characterized by an alternation of morphostructural ridges with steep slopes of tectonic origin (i.e. fault line scarp) and Quaternary tectonic depressions. The belt tops frequently comprise remnants of ancient erosional land surfaces, raised by the Quaternary uplift and dismembered by Quaternary faults (Schiattarella et al. 2003, 2006). Consequently, these erosional land surfaces are arranged in several superimposed orders, hanging with regard to the axial zone basins (Schiattarella et al. 2003, 2006). Such tectonic depressions are mainly filled with lacustrine and alluvial deposits of Quaternary age. They are crossed by longitudinal (i.e. parallel to the long-axis of the basins) V-shaped valleys, with thalwegs generally ranging between 500 and 700 m a.s.l. The belt tops are frequently characterized by remnants of ancient erosional land surface, suspended by Quaternary regional uplift and dismembered by Quaternary fault activity. Consequently, the erosional land surfaces are arranged in several superimposed orders (Schiattarella et al. 2003, 2006). As a consequence of the former erosional stages, the paleosurfaces are low-relief and high-altitude relict geomorphological features (Schiattarella et al. 2003, 2006).

The study area coincides with one of the widest hydrographic catchments of the axial zone: the lower Tanagro River valley (Fig. 1), which longitudinally crosses a portion of the Auletta basin (after Ascione et al. 1992) after having run through the Vallo di Diano valley. The Auletta basin is a N120°–130°-trending fault-bounded depression filled with a very thick Neogene-Quaternary marine to continental clastic succession (Amato et al. 1992; Ascione et al. 1992; Gioia & Schiattarella 2010). Seismic data showed that the clastic infill is at least 500 m thick in the basin depocentral area (Amicucci et al. 2008). The outcropping stratigraphic succession is mainly constituted by several hundred meters of continental deposits which unconformably overlay Lower–Middle Pliocene marine to transitional sediments. The oldest Pliocene marine deposits are more significantly present in the Mt Marzano area. The following (400–500 m thick) continental succession is composed of several generations of lacustrine, fluvial, and travertine deposits ranging in age from Late Pliocene to Middle Pleistocene. The master fault of the Auletta basin is a NE dipping high-angle listric fault, located at its south-western margin. Along the entire area, the Pliocene and Quaternary clastics are tilted towards the south-west and displaced by the strike-slip to extensional NW–SE trending multisplay fault bordering the Alburni Mts. Moreover, due to the Quaternary uplift and the border-fault activity, both the basin filling clastic sequences and the surrounding carbonate massifs have been deeply incised by the fluvial network. Besides faulting and tilting, both the limestone bedrock and the Pliocene and Quaternary clastics of the basin infill are featured by several orders of terraced surfaces.

From a geomorphological point of view, the study area is characterized by two impressive carbonate massifs bordered by steep slopes and deeply incised by transversal streams. The landscape of the massifs is characterized by remnants of erosional land surfaces, organized in several generations and related to different ancient base levels of erosion. The south-western sector of the basin has an impressive topography controlled by the Pliocene to Quaternary activity of the fault systems of the south-western margin of the basin. The north-eastern flank of the depression is topographically more articulated, being organized into minor synthetic and antithetic faults. Landslides are not widespread in the basin, being located only in some sectors of the right orographic side of the valley, where clay deposits largely crop out.

Methods

A detailed study of relict (i.e. hanging upon the present-day thalwegs) erosional land surfaces and fluvial terraces has been performed by field survey, map analysis and aerial photo interpretation in order to reconstruct the ancient base levels of erosion and the landscape evolution of the Auletta basin and surrounding carbonate massifs. Age constraints of the morphotectonic markers (i.e. geomorphological features with a known geometry that can be used to track landscape evolution, Burbank & Anderson 2001) have been obtained by the re-interpretation of apatite fission track data (Aldega et al. 2005; Mazzoli et al. 2008), combined with geological information and morphostratigraphic analysis together with radiometric dating. Radiometric dating consists of both apatite fission track data from rocks belonging to different tectonic units of the axial zone of the southern Apennines (Aldega et al. 2005; Mazzoli et al. 2008) and ^{40}Ar/^{39}Ar dating of sanidine crystals from tephra layers interbedded into the Vallo di Diano lacustrine succession (Karner et al. 1999; Di Leo et al. 2009). Mean altitudes of morphotectonic markers have been used as reference levels for the estimation of eroded volumes (Amato et al. 2003; Martino et al. 2009).

Additional data about denudation rates related to the recent/active geomorphological system have been obtained by estimating the amount of suspended sediment yield of channels on the grounds of empirical relationships based on the hierarchic arrangement of the fluvial network (Schiattarella et al. 2006; Della Seta et al. 2007). These empirical equations were originally obtained by an extensive study performed by Ciccacci et al. (1980), which statistically correlated the values of measured suspended sediment yield at the outlets of several Italian catchments to some geomorphic and climatic parameters (see § *Morphometric analysis of the drainage network and indirect estimation of denudation rates*).

Long- and short-term denudation rates obtained through these methods have been compared with the sedimentation rates calculated from two adjacent endorheic basins (the Pantano di San Gregorio and the Vallo di Diano basins, Fig. 2) on the basis of published chronological constraints provided by tephrochronological data (Karner et al. 1999; Aiello et al. 2007). This dataset has also been compared with the sedimentation rates calculated by de Vente et al. (2006) for the historical sediment deposition in a small catchment located in the northern sector of the study area (de Vente et al. 2006), as well as with the uplift rates of the study area and the regional long-term exhumation data provided by thermochronometry (Aldega et al. 2005; Mazzoli et al. 2008). Apatite fission track analysis (AFTA) furnished additional data concerning the time and rates of cooling related to exhumation in the uppermost part of the crust (i.e. below the 110 °C isotherm). Thermal histories of rocks belonging to different tectonic units of the southern Apennines chain have been used in combination with geology and morphotectonic analysis to define both the amounts and timing of denudation and/or uplift. An absolute chronology may be defined by combining the onset and duration of cooling events estimated from AFTA with stratigraphical data (i.e. hiatuses in the stratigraphy, age of the syntectonic basins) and the formation of erosional surfaces on a regional scale. Since the onset of the cooling episode determined from apatite fission track data agrees with the relative timing for the formation of the regional paleosurface in the southern Apennines, we infer that both the cooling event and the erosional land surface are evidence of the same episode of exhumation (note that the AFT cluster is comprised between 2 and 3 Ma, as well as that the mid-Pliocene sediments are the youngest deposit involved in the ancient planation process). A similar approach has recently been used in different tectonic settings and geodynamic contexts (Gunnell 1998; Schoenbohm et al. 2004; Bonow et al. 2006; Japsen et al. 2006).

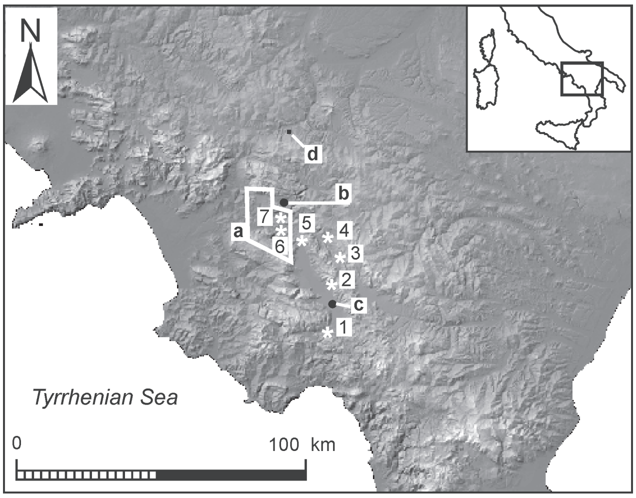


Fig. 2. DEM of the southern Apennines chain and location of the study area. The Auletta basin is represented in the white box a). Black circles indicate the cores of the Pantano di San Gregorio Magno basin b), and the Vallo di Diano basin c), and the artificial reservoir of the Muro Lucano town d). The stars indicate the studied stratigraphic sections: **1** — Buonabitacolo; **2** — Grotta S. Angelo; **3** — Brienza; **4** — Serre Piane; **5** — Cangito; **6** — Auletta; **7** — Portola.

Age constraints of morphotectonic markers and missing volumes estimation

Reconstruction of paleotopography and identification of ancient base levels of erosion in the Auletta basin were performed through a detailed geomorphological study of relict (i.e. hanging upon the present-day thalwegs) erosional land surfaces and fluvial terraces. The reconstructed paleomorphology allowed us to obtain estimates of eroded volumes (Fig. 3) from the ancient morphology inferred from morphotectonic markers (Amato et al. 2003; Schiattarella et al. 2008; Martino et al. 2009; Pérez-Peña et al. 2009). The estimation of eroded volumes in the drainage network of the Tanagro River lower valley was perfomed through a GIS-aided calculation supported by a SRTM-DEM, using the order of erosional land surfaces more chronologically constrained (i.e. the S3 erosional land surfaces). The mapped remnants of relict geomorphological land surfaces have been interpolated by TIN (triangulated irregular network) and subtracted pixel by pixel to the present-day topography. Then, denudation rates were calculated on the basis of the relative age (*sensu* Watchman & Twidale 2002) assigned to the morphotectonic markers (mainly land surfaces and paleosols). The geomorphological mapping of relict sub-horizontal surfaces (i.e. hanging erosional land surfaces and fluvial terraces) and their relationships with tectonic lineaments and Quaternary deposits provided consistent information on the long-term landscape evolution, whereas the reinterpretation of data from apatite fission track analysis furnished further chronological constraints (Aldega et al. 2005; Schiattarella et al. 2006; Mazzoli et al. 2008). The uplift history of the summit palaeosurface has been derived by studying the stratigraphical and morphostructural evolution of some intermontane basins located along the axial zone of the Apennine chain (Auletta, Melandro, and Vallo di Diano basins). Moreover, other chronological constraints have been obtained by the radiometric dating of tephra and paleosols interbedded in the continental deposits of the Auletta and Vallo di Diano basins (Di Leo et al. 2009).

Denudation rates have been estimated from the elevation and de-activation age of the erosional surfaces referred to the ancient base level. The eroded rock volume below a reference surface is evaluated and the corresponding denudation rate is computed as follows:

$$Dr = V/A * T_d \qquad (1)$$

where Dr is the denudation rate, V the eroded volume, A the area below the reference surface and T_d the de-activation age of the reference land surface. It is worth noting that the methodological approach based on the estimation of eroded volumes is based on the assumption that the erosional processes were dominant with respect to the depositional ones after the morphological de-activation of the chosen morphotectonic markers (Martino et al. 2009).

The reconstruction of paleorelief and the evaluation of the eroded volumes have been performed for the entire drainage basin using the plano-altimetric distribution of the S3 erosional land surfaces, chronologically constrained at ca. 0.8–0.6 Ma on the grounds of radiometric dating. Such an estimation is supported by a DEM extracted by SRTM (Shuttle Radar Topography Mission) altimetric data and is based on a subtraction pixel by pixel between the reconstructed paleomorphology and the present-day topography. After the surface uplift of the S3 land surface, the amount of sedimentation in the basin is negligible, being restricted to small bodies of alluvial, colluvial and slope deposits. Thus, it is likely that erosional processes are prevalent after the de-activation of the S3 erosional land surfaces.

To get more information about fluvial incision and erosional processes at a sub-basin scale, a similar approach (i.e. based on the estimation of eroded volumes) has been applied to several key sectors of the study area, using 1:25,000 scale topographic maps and DEMs with a spatial resolution of 20 m. The selected sub-basins represent all the sectors of the drainage basin, being illustrative of the different geomorphological and litho-structural settings. In addition, they are characterized by the dominance of erosional processes rather than the depositional ones and by a good preservation of the morphotectonic markers used as a reference level along the valley flanks.

In the case of the small endorheic basin of the Pantano San Gregorio Magno and surrounding mountains, the reconstruction of the bedrock top was attempted on the basis of the thickness of the Middle Pleistocene to Holocene lacustrine deposits and the interfingered alluvial fan sediments (Aiello et al. 2007). As the available cores did not reach the bedrock, a filling thickness of 150 m has been deduced assuming a mean sedimentation rate of 0.3 mm/yr (Aiello et al. 2007), taking into account the mid-Pleistocene genesis of the basin.

Morphometric analysis of the drainage network and indirect estimation of denudation rates

An indirect estimation of the erosion processes related to the recent and modern geomorphological system was performed on the basis of the planimetric and planar geometry of the drainage network. The drainage pattern in tectonically active

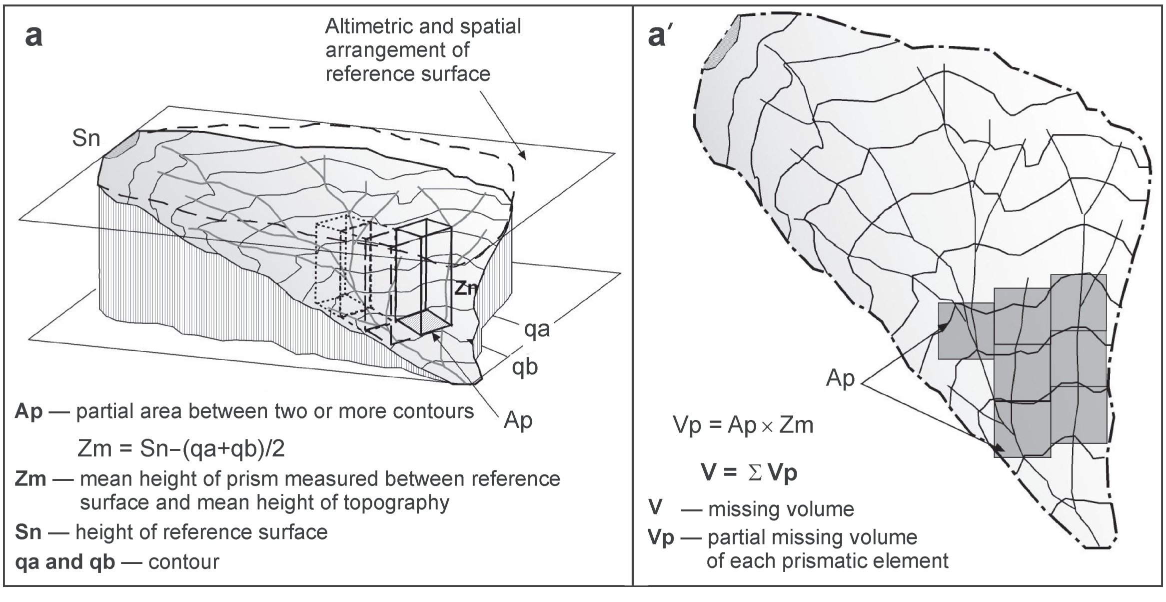


Fig. 3. Sketch of the method used for the calculation of the eroded rock volume in some catchment basins of the lower valley of the Tanagro River. The method is based on altitude difference between reference surface and present-day topography.

regions is very sensitive to perturbations induced by both tectonics and climate processes (Avena et al. 1967; Firpo & Spagnolo 2001; Beneduce et al. 2004; Capolongo et al. 2005; Della Seta et al. 2007; among others). Several authors demonstrated that geomorphic indexes are very helpful for assessing the strong sensitivity of the fluvial system to tectonic and climate processes responsible for accelerated river incision, asymmetries of the catchments, and river diversions. Indeed, these morphometric parameters are related to the influence of tectonics, lithology and climate on the development and arrangement of fluvial channels (Capolongo et al. 2005; Pedrera et al. 2009; Gioia & Schiattarella 2010; Pérez-Peña et al. 2010). In this work, morphometric analysis allowed us to calculate several parameters of the drainage network which were used to estimate fluvial turbid transport data, an expression of the degree of the erosion within the drainage basin (Avena et al. 1967; Schiattarella et al. 2006, 2008; Della Seta et al. 2007). More specifically, empirical relationships linking the *Tu* (mean annual suspended sediment yield) with morphometric parameters of the drainage network such as *drainage density* and *hierarchical anomaly density* (Ciccacci et al. 1980; Della Seta et al. 2007) were used. The values of the *Tu* index estimated by this equations can be considered a proxy for midterm (i.e. Holocene) denudation rates although it present some problems. Indeed, this estimation does not include the amount of channel bedload, which is small part of the total solid load in the Mediterranean region (Newson 1981). On the other hand, small catchments draining the high-relief mountain region of the axial zone of southern Italian Apennines can have a higher percentage of bedload (Rovira et al. 2005). Furthermore, it is worth noting that the estimation of sediment discharge may be representative of the recent (i.e. Holocene) to present-day geomorphological system.

The drainage network of the studied areas was derived from 1 : 25,000 scale I.G.M.I. topographic maps and aerial photo-interpretation. All the channels were classified according to the Strahler (1957) hierarchic scheme and the following morphometric parameters have been evaluated for each sub-basin: *bifurcation ratio* ($Rb = N_u/N_{u+1}$ where N_u and N_{u+1} are the number of streams per order u and u + 1, respectively; Strahler 1957), *direct bifurcation ratio* ($Rbd = N_{du}/N_{u+1}$ where N_{du} is the number of streams of u order which flow in u + 1 order and N_{u+1} is the number of streams per order u and u + 1, respectively; Avena et al. 1967), *bifurcation index* ($R = Rb - Rbd$, where *Rb* and *Rbd* are the *bifurcation ratio* and the *direct bifurcation ratio*, respectively; Avena et al. 1967), *hierarchical anomaly number* (*Ga*, the number of I order streams which make the drainage network perfectly hierarchized, i.e. with a value of $N_{du} = N_u$; Avena et al. 1967), *hierarchical anomaly index* ($\Delta a = Ga/N_1$ where *Ga* is the *hierarchical anomaly number* and N_1 is the number of I order streams; Avena et al. 1967), *hierarchical anomaly density* ($ga = Ga/A$ where *Ga* is the *hierarchic anomaly number* and *A* is the area of the sub-basins; Avena et al. 1967).

All these indices are widely used by the Italian workers as indicators of the degree of organization of the drainage network which is controlled by several factors such as tectonics, lithology, climate, topography. For example, a well organized hydrographic catchment (e.g. developed in a tectonically inactive and lithologically uniform area) tends to assume low values of some morphometric parameters (e.g. *Rb* and *Rbd* close to 1; *R*, *Ga* and Δa close to 0). On the contrary, several authors have demonstrated that the same parameters generally assume high values in catchments fairly organized as a consequence of recent perturbations due to tectonics, geomorphological processes and climate variations (Firpo & Spagnolo 2001; Beneduce et al. 2004; Capolongo et al. 2005; Gioia & Schiattarella 2006, 2010). In particular, anomalous confluences (i.e. channels of *u* order which are not flowing in channels of order *u + 1*) are widely diffused in drainage basins highly perturbed by tectonic or geomorphological processes (Avena et al. 1967; Gioia & Schiattarella 2006). In this paper, such indices have been calculated for the entire drainage basin and for each sub-basin in order to evaluate the *Tu* (mean annual suspended sediment yield), using the empirical relationships proposed by Ciccacci et al. (1980). In particular, the following relation has been used:

$$Log\ Tu = 1.82818\ Log\ D + 0.01769ga + 1.53034 \qquad (2)$$

where *Tu* is the fluvial turbid transport (the mean annual sediment yield transported in suspension per unitary area of the basin), *D* is the drainage density and *ga* is the *hierarchic anomaly density*.

The values of the *Tu* index within the hydrographic catchment of the lower Tanagro River valley may be considered as an indicator of denudation intensity. Giving a bulk density to the sediments outcropping in the drainage basin, it is possible to convert the *Tu* index into mean denudation rates. More specifically, the conversion of *Tu* values into denudation rates (*Ta*) has been obtained as follows:

$$Ta = (Tu/\rho) * 10^{-3} \qquad (3)$$

where *Tu* is the estimated mean annual suspended sediment yield and ρ is the mean bulk density assigned to every sub-basin. The areal distribution of outcropping lithology within each sub-basin has been assessed and a mean value of density reflecting the lithological features was assigned according to the values proposed by Tiberti et al. (2005).

Results

Geomorphological and chronological constraints on paleotopographic reconstruction

Long-term landscape evolution of the Auletta basin results from the interaction between tectonic and geomorphological processes, largely controlled by regional uplift, fault activity and climate changes. The morphostructural evolution of the Auletta basin is characterized by stages of tectonic uplift and fault activity alternating with periods of sculpting of erosional land surfaces and deposition of sedimentary bodies with gently dipping tops (alluvial fans and flood), both related to the different past base levels of the trough. In the catchment basin, four generations of erosional land surfaces (Fig. 4), carved in both limestone bedrock and Pliocene-Quaternary clastic sedi-

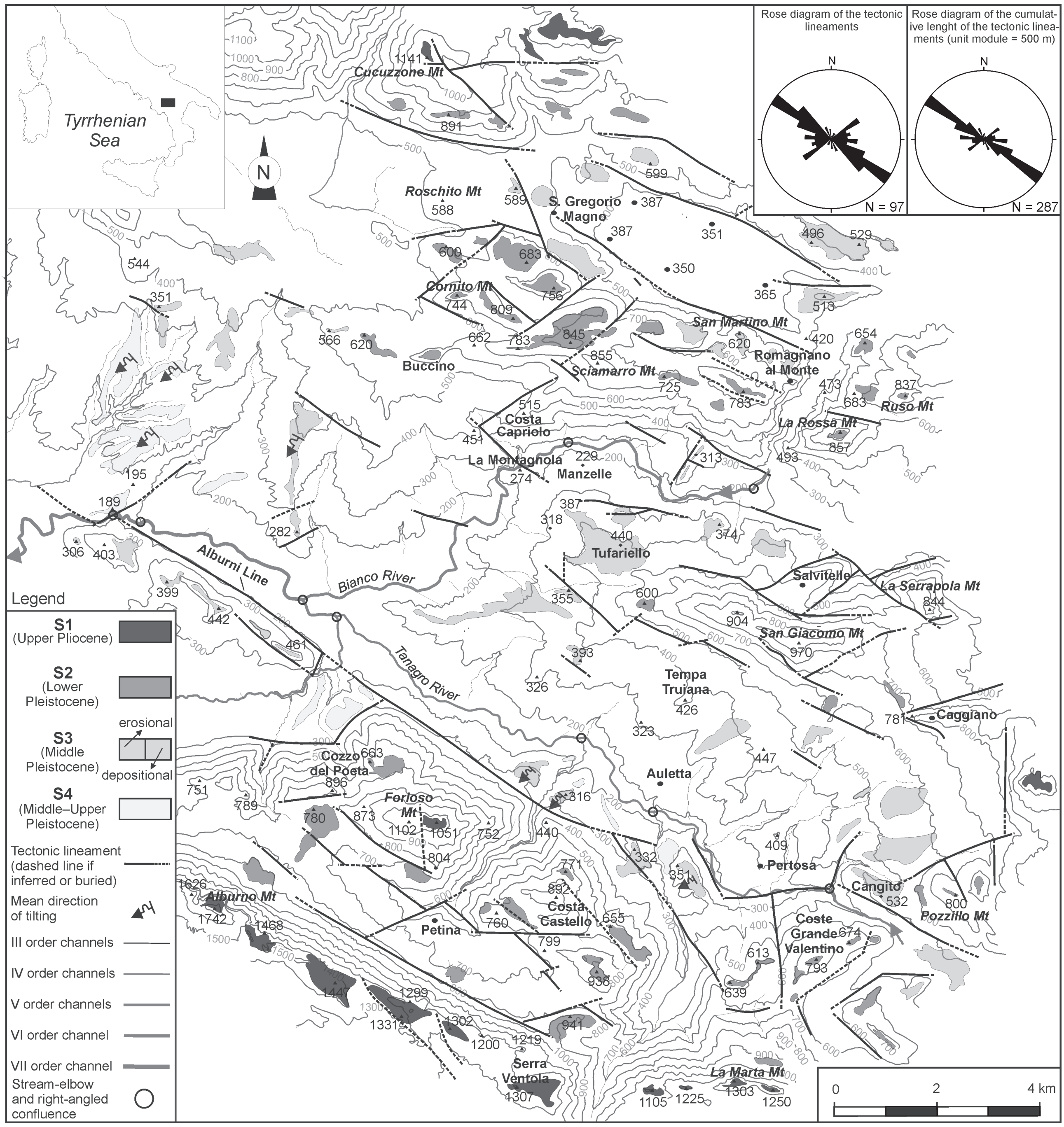


Fig. 4. Morphostructural map and plano-altimetric arrangement of the several orders of erosional land surfaces from the Auletta basin area. Rose diagrams are constructed on the basis of frequency (left) and cumulative length (right) of azimuthal orientations of tectonic lineaments.

ments of the basin infill, are recognized. The relative ages of these erosional land surfaces are summarized in Fig. 5. The highest land surfaces (summit paleosurface, or S1 in Fig. 4) represent the morphological remnants of a regional planated landscape. They unconformably cut across tilted Mesozoic limestones and Lower-Middle Pliocene marine sediments. Apatite fission track data from rocks belonging to different tectonic units of the axial zone of the southern Apennines (Aldega et al. 2005; Mazzoli et al. 2008) indicate a concordant final cooling age of ca. 2.5–2.6 Ma (average value, Schiattarella et al. 2009), suggesting a widespread exhumation during the Late Pliocene. This relatively young exhumation is likely to be related to erosional denudation rather than tectonics (i.e. low-angle extension, as suggested by other authors for older stages, see Schiattarella et al. 2006), thus implying a Late Pliocene stage widely affected by intense exogenetic processes. It can be argued that such a regional denudation could be related to the summit paleosurface morphogenesis. The attribution of those features to the Late Pliocene is strengthened by the presence of Lower–Middle Pliocene clastic deposits

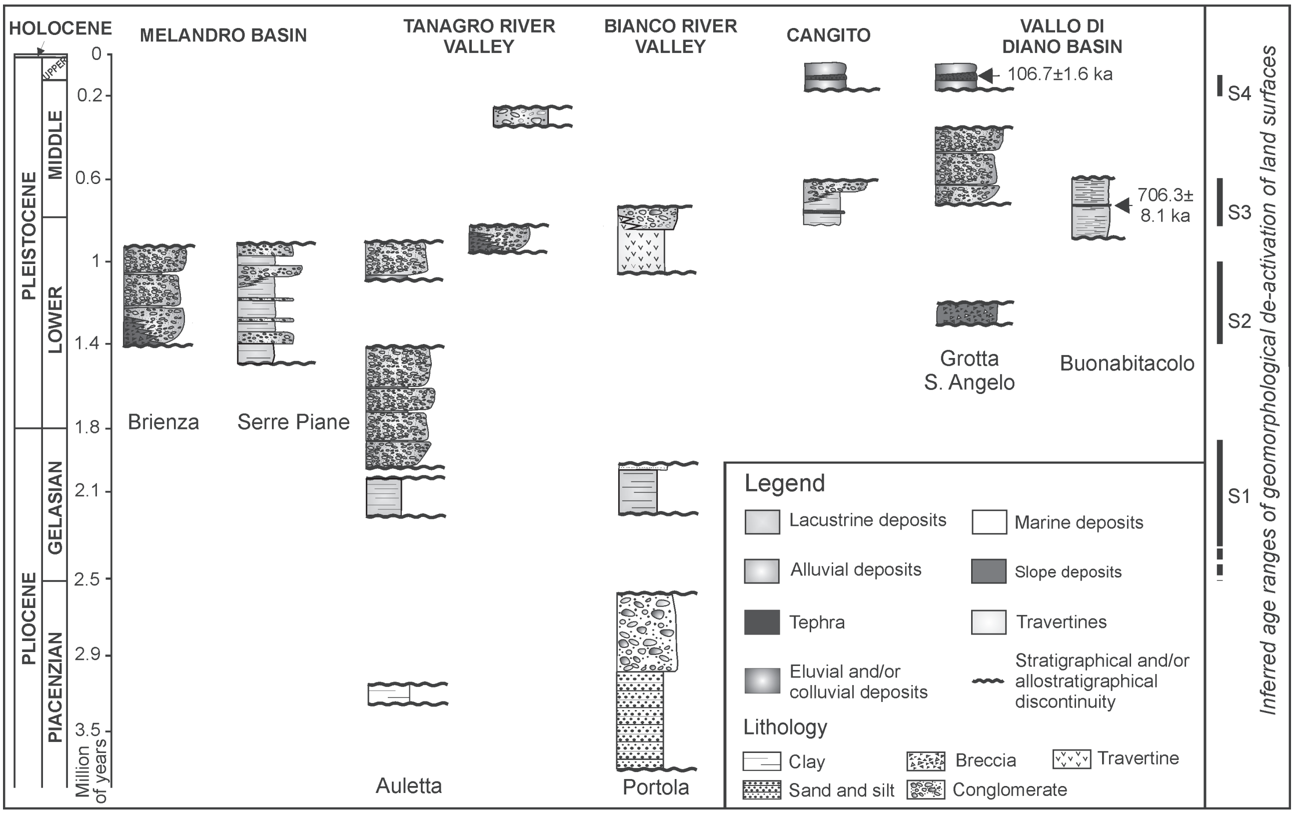


Fig. 5. Stratigraphic correlations among different logs from Vallo di Diano, Auletta and Melandro basin. The inferred ages of de-activation of the several generations of the erosional landsurfaces are also shown.

outcropping on the top of the Maddalena Mts (Schiattarella et al. 2003) and in the Mt Marzano area, involved in the planation of the paleosurface. Based on the assumption that the regional uplift and fault activity related to the tectonic stage responsible for the morphological de-activation of that ancient land surface created the accommodation space for continental infill of the intermontane catchments, the regional correlation of the stratigraphic successions from different basins can provide chronological constraints to better identify the age of the first significant vertical movements (Fig. 6). This vertical motion is responsible for the geomorphological de-activation of the paleosurface and its uplift, whereas pervasive faulting and fluvial erosion are accountable for its subsequent fragmentation (Martino et al. 2009). According to all the evidence, it is possible to assign a Late Pliocene age to the oldest paleosurface (i.e. S1 in Fig. 4) of the Alburni and Mt Marzano massifs, generally found above 1100 m a.s.l. The S2 erosional land surfaces (Fig. 4) frequently represents dislocated remnants of the oldest one and their chronological attribution to the Early Pleistocene is corroborated by the presence of Lower Pleistocene fluvial conglomerates in a small relic of this erosional land surface in the western sector of the Mt San Giacomo. The S3 erosional surfaces (Fig. 4) can be laterally correlated with a fluvial terrace cutting the Lower-Middle Pleistocene lacustrine deposits of the Vallo di Diano basin (Fig. 5). Then, the genesis of the S3 surfaces represents a geomorphic stage immediately following the deposition of the lacustrine deposits of the Vallo di Diano basin. Since these deposits have been radiometrically dated to 0.706 Ma in the uppermost stratigraphic levels (Di Leo et al. 2009), the S3 land surface can be reasonably referred to the Early Pleistocene–Middle Pleistocene time-span. The youngest generation of erosional/depositional surfaces (S4 in Fig. 4) — well preserved in the western tip of the valley and in the Torrente Petroso valley — is morphologically inserted into the older erosional surfaces and cut into the youngest deposits (ascribed to the upper part of the Middle Pleistocene — Buccino et al. 1978; Gioia & Schiattarella 2010) outcropping in the basin. The uplift-induced dissection of S4 land surfaces can be attributed to a regional tectonic event occurring at the Middle to Late Pleistocene transition (Bordoni & Valensise 1998), detected also in the adjacent Sele Plain (Amato et al. 1991) and likely responsible for the subsequent tilting of the westernmost land surfaces.

The long-term denudation rates obtained using the order of relict land surfaces better constrained in the study area (S3 erosional landsurfaces, mean elevation of 530 m a.s.l., uplift age of 0.8–0.6 Ma) are 0.22–0.29 mm/yr, in good agreement with data calculated at the regional scale, on the grounds of cartographic, GIS-aided and/or morphometric methods (Schiattarella et al. 2008; Martino et al. 2009). The mean denudation rates estimated at the sub-basin scale are roughly settled on similar values, being included within a narrow range of 0.14–0.24 mm/yr (Fig. 7). Weak increases of denudation rates have been recorded for both reference levels of the Early Pleistocene and Late Pleistocene. Low data variability indicates a good consistency of acquired datasets. Denudation

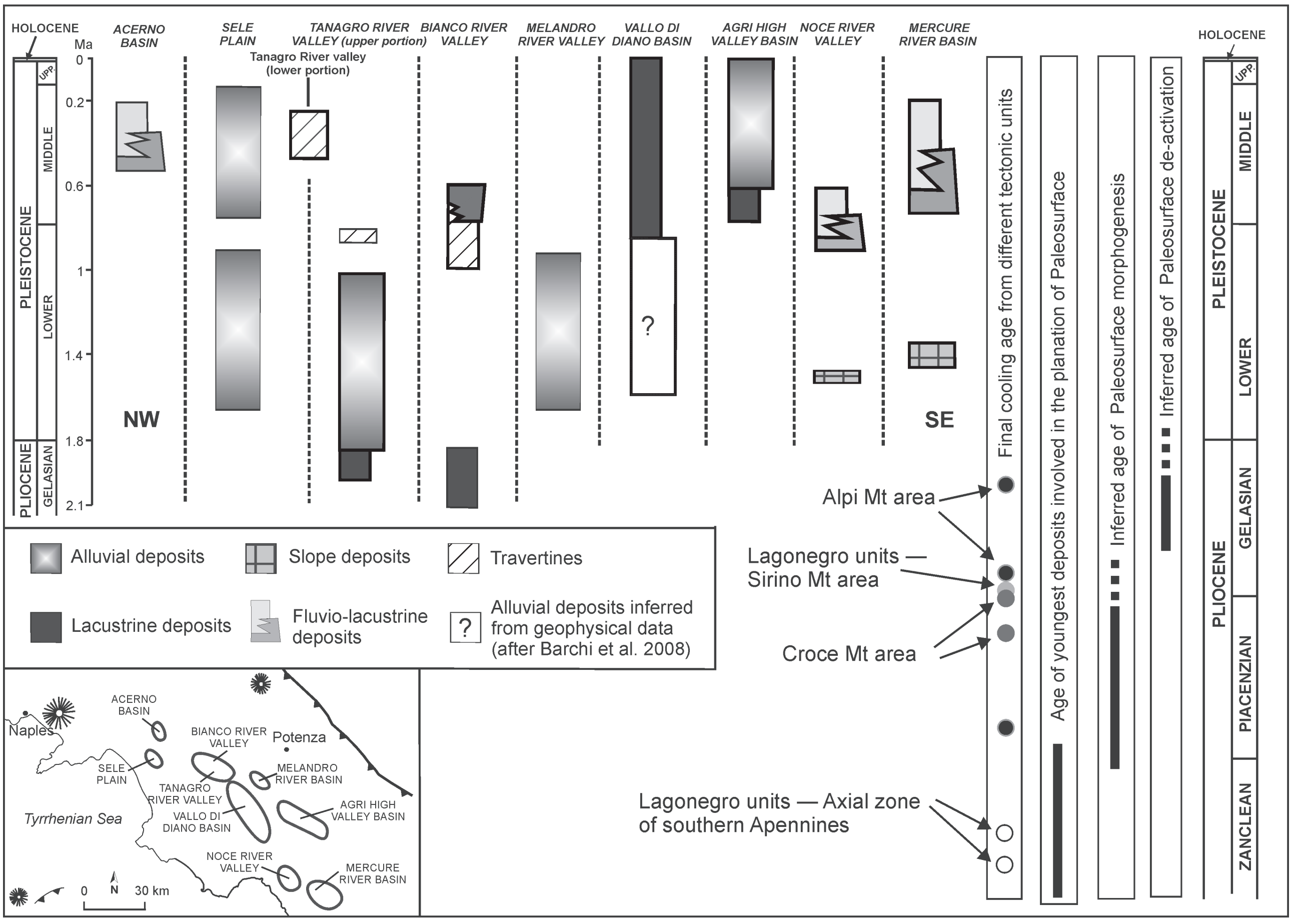


Fig. 6. Stratigraphic successions from different basins of the axial zone of the southern Apennines, AFT data and chronological constraints on the age of the summit paleosurface.

rates from the Pantano San Gregorio Magno basin and surrounding mountain ranges from 0.07 to 0.13 mm/yr, thus showing the lowest values in the investigated area. The small catchment of the Pantano San Gregorio Magno basin is characterized by transverse channels joined to the local base level of the endorheic depression, located at a higher elevation than ancient and present-day thalwegs of the main stream. Due to this peculiar feature of the river longitudinal profiles, the efficacy of fluvial incision in this area has been limited with respect to the adjacent sectors of the Tanagro River drainage basin.

Drainage basin and mean annual suspended sediment yield (Tu) estimation

The drainage basin covers an area of about 300 km^2 (Fig. 8) and has a planimetric shape stretched in WNW–ESE direction. The fluvial network developed mainly on shallow-water carbonates and fluvial conglomerates (Fig. 1). Consequently, it is characterized by low values of drainage density (mean value of 2.33) and by a low hierarchical organization. The drainage network is more developed in the western sector of the catchment, where terrigenous (siliciclastic) deposits largely crop out (Figs. 1 and 8).

The main streams of the area (e.g. Tanagro and Bianco Rivers) cut deeply into the Pliocene-Quaternary deposits and follow the trend of the border faults with a planimetric arrangement roughly rectilinear (Fig. 1). The main tributaries generally run in narrow V-shaped valleys, where incision processes have prevailed over the depositional ones. Confluences are frequently right-angled and high-angle stream-elbows are frequent (Fig. 4). The activity of the Alburni Mts master fault provoked a lateral shift of the Tanagro River toward the south-western side of the valley, as also demonstrated by morphometric analysis of the drainage net (Gioia & Schiattarella 2010). Such a migration favoured the development of an asymmetric valley and it is also confirmed by independent morphostratigraphic data such as the migration of the recent depocenter of the basin toward the north-western sector and the tilting of the Middle to Upper Pleistocene S4 land surface located in that sector of the basin (see also Buccino et al. 1978). Moreover, the values of the morphometric parameters also suggest a significant structural influence on the arrangement of the main streams. As a matter of fact, the highest values of the bifurcation ratio (*Rb*), direct bifurcation ratio (*Rbd*), and bifurcation index (*R*) were found in the major sub-basins.

Apart from the relationships between tectonics and fluvial network evolution, morphometric analysis of the drainage

Subbasin		Strahler's order	Reference level (Sn)	T_d (Ma) De-activation Age	Mean height of Sn (m)	A (km^2) Subbasin area	V (km^3) Eroded volumes	Dr (mm/yr) Denudation rates	Tu (T/km^2/yr) Mean annual suspended sediment yield	Ta (mm/yr) Denudation rates from converted Tu
B2	Valle Vadursi	4	S1	2.2–1.8	1180	4.375	2	0.21–0.25	97	0.04
G	Vallone del Cangito	4	S1	2.2–1.8	1115	8.125	3.1	0.17–0.21	169	0.06
Pantano di San Gregorio Magno		4	S1	2.2–1.8	1100	31.875	4.3	0.06–0.08	59	0.02
H	Vallone S. Onofrio	4	S2	1.4–1	840	4.38	1.408	0.23–0.32	141	0.05
I	Torrente Lontrano	4	S2	1.4–1	925	8.75	3.8	0.31–0.43	184	0.07
B1	Vallone del Ceraso	4	S2	1.4–1	860	7	2	0.20–0.29	69	0.03
Pantano di San Gregorio Magno		4	S2	1.4–1	830	25.875	2.2	0.06–0.09	59	0.02
G	Vallone del Cangito	4	S3	0.8–0.6	540	1.375	0.12	0.11–0.15	169	0.06
Q	Torrente Ficarrola	3	S3	0.8–0.6	540	2.68	0.3	0.14–0.19	127	0.06
Pantano di San Gregorio Magno		4	S3	0.8–0.6	560	9.20	0.6	0.08–0.11	59	0.02
A2	Torrente Petroso	5	S4	0.2–0.1	275	5.5	0.262	0.24–0.48	204	0.07

Endorheic basins	Age	Depth	*Sedimentation rates*
Pantano di San Gregorio Magno basin	0.17	51	**0.30**
Vallo di Diano basin	0.596	142	**0.24**
	Ma	m	**mm/yr**

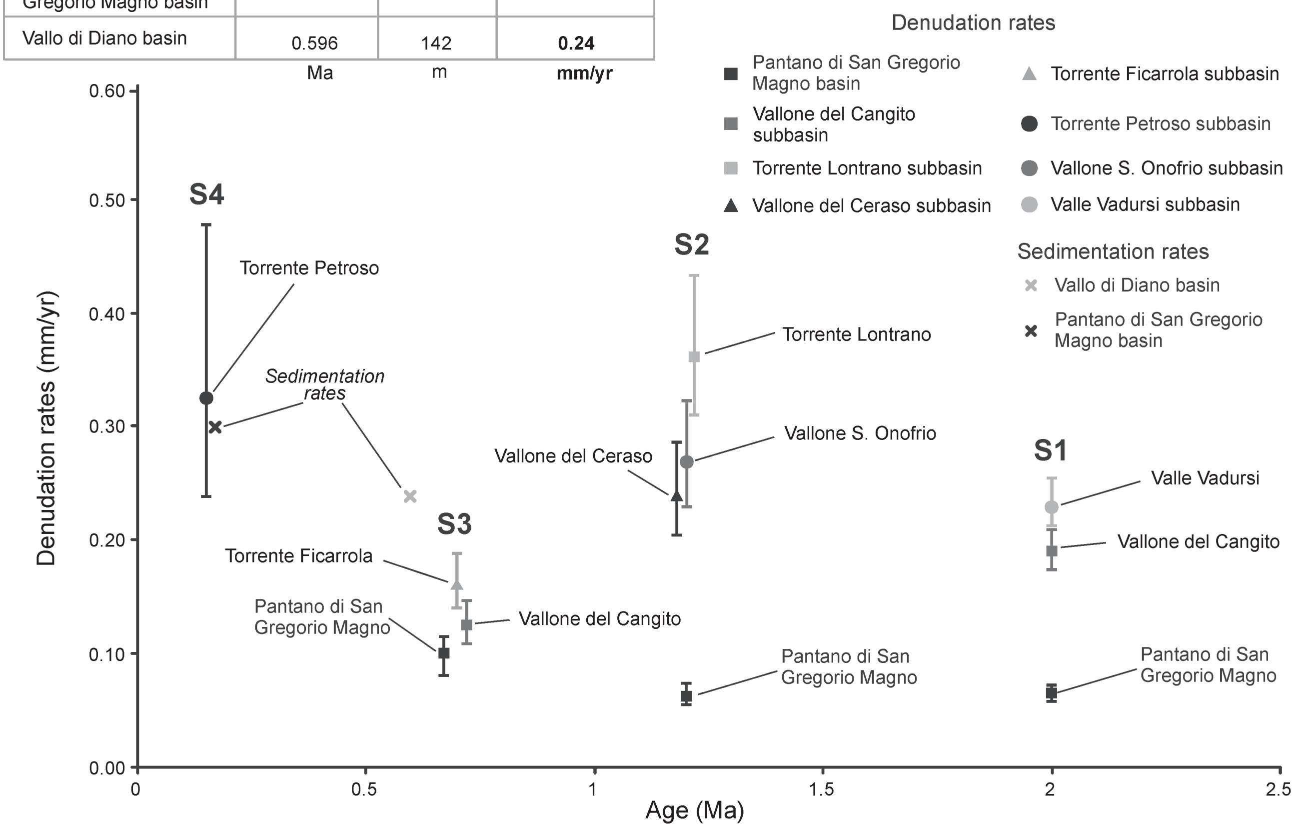
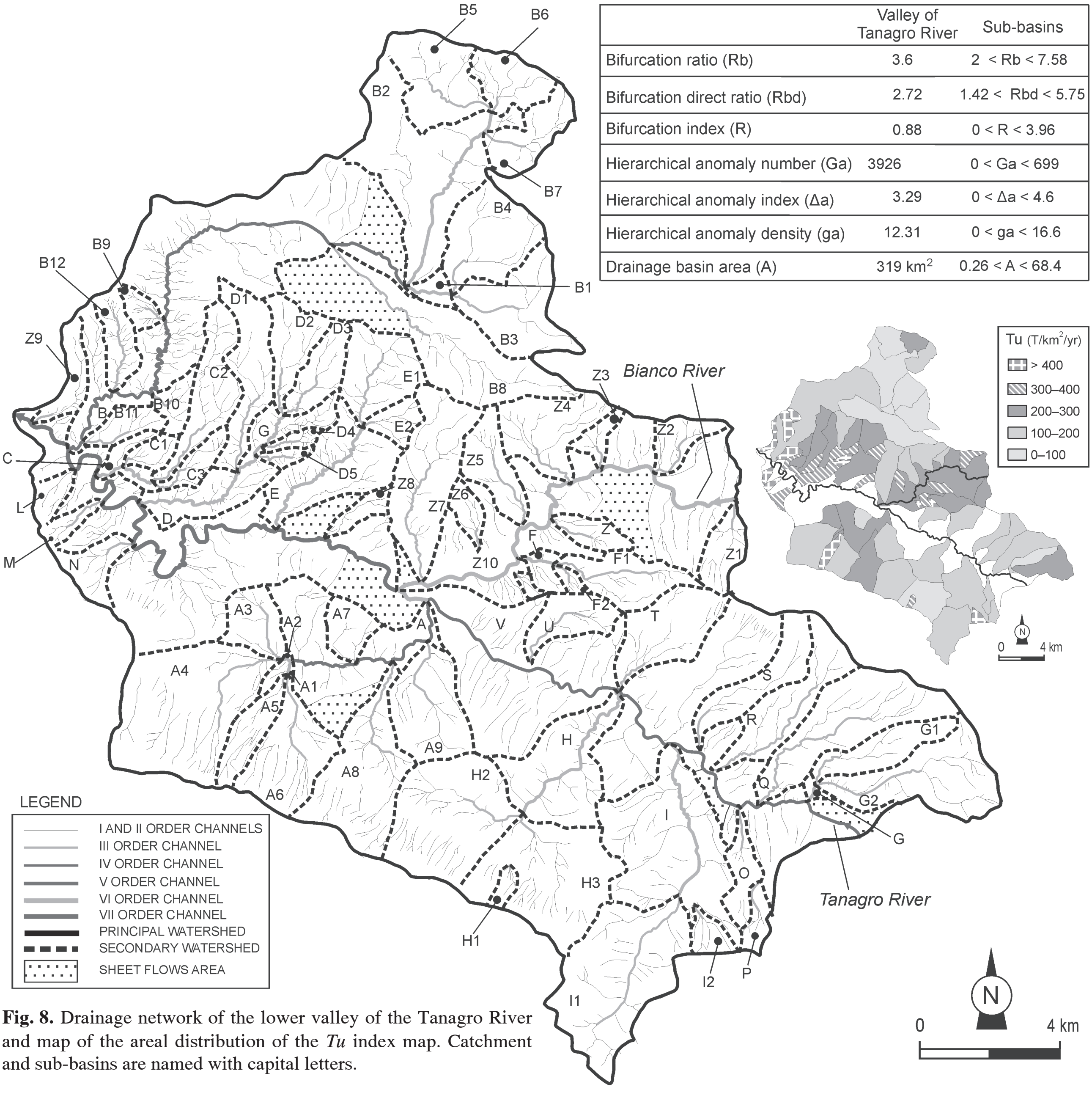


Fig. 7. Tables and diagram of the denudation and sedimentation rates calculated in some key areas of the lower valley of the Tanagro River basin.

basin allowed us to estimate the *Tu* index (cf. § *Morphometric analysis of the drainage network and indirect estimation of denudation rates*) for every sub-basin of the studied drainage basin. The values of the *Tu* index showed a wide variability, ranging from 67 (B8 sub-basin) to 1342 (D5 sub-basin) t/km^2/yr. The higher *Tu* values (>700 t/km^2/yr with peaks of 1200–1300 t/km^2/yr) were recorded in small catchments of the easternmost part of the drainage basin (B10, B12, Z9, D4, and D5 sub-basins) and in some small sub-basins of the left side of the Bianco River (F2 and V sub-basins). Both these sectors are characterized by clay or shale deposits, a well developed drainage network and some landslides. The mean value of the *Tu* index for the entire drainage area is 301 t/km^2/yr while the lowest values of less than 100 t/km^2/yr are typically concentrated in sub-basins where carbonate rocks and conglomerate deposits crop out. The



	Valley of Tanagro River	Sub-basins
Bifurcation ratio (Rb)	3.6	2 < Rb < 7.58
Bifurcation direct ratio (Rbd)	2.72	1.42 < Rbd < 5.75
Bifurcation index (R)	0.88	0 < R < 3.96
Hierarchical anomaly number (Ga)	3926	0 < Ga < 699
Hierarchical anomaly index (Δa)	3.29	0 < Δa < 4.6
Hierarchical anomaly density (ga)	12.31	0 < ga < 16.6
Drainage basin area (A)	319 km^2	0.26 < A < 68.4

Fig. 8. Drainage network of the lower valley of the Tanagro River and map of the areal distribution of the *Tu* index map. Catchment and sub-basins are named with capital letters.

lowest values of the *Tu* index (< 100 t/km^2/yr) have been recorded in sub-basins draining calcareous areas of the Marzano and Alburni massifs (B2, B3, B4 and B5 and H3 sub-basins), Holocene palustrine deposits (B8 sub-basin) and conglomerate deposits (G1 sub-basin). Catchments with travertine outcrops have *Tu* values of about 110–130 t/km^2/yr, as well. The areal distribution of the *Tu* index in the whole drainage basin showed a strong correlation with lithology. The carbonate sub-basins are characterized by few channels deeply incised into the bedrock with high gradients. In such a geomorphological setting, it is likely that most of the sediments are transported, during rainstorm events, as bedload by ephemeral channels. Therefore, using a *Tu*-based evaluation, some underestimation of real erosion processes can be hypothesized.

Assuming a bulk density of sediments ranging from 2200 to 2700 kg/m^3 (Tiberti et al. 2005) the function of the spatial arrangement of the different deposits in every single sub-basin, the mean denudation rates (*Ta*, Fig. 7) for the entire drainage area correspond to about 0.12 mm/yr.

Comparison between denudation, sedimentation, uplift, and exhumation rates

Denudation rates obtained from paleotopographic reconstruction and from the indirect estimation of suspended sediment yield have been compared with the long- and short-term sedimentation rates estimated from the sedimentary sequences filling intermontane basins and from the deposits filling a reservoir, with the local uplift rates, and with the regional exhumation rates.

Reservoir sedimentation data for a small catchment (50 km^2) located a few kilometers north of the study area, provided useful information on historical sediment accumulation. The catchment showed a well developed fluvial network and is characterized by wide outcrops of terrigenous deposits affected by mass movements. The resulting sediment yield of the reservoir is 1570 t/km^2/yr corresponding to mean denudation rates of 0.5–0.6 mm/yr with a rock density of 2.6 g/cm^3 (Fig. 9). The drainage network pattern, litho-structural setting and geomorphological features of this catchment are quite similar to those of the sub-basins of the Tanagro River drainage network characterized by the higher values of *Tu* index. Then, a good correlation of the mean denudation rates calculated in these two cases can be stressed. This interpretation is confirmed by the strong increase of the *Tu* values in areas affected by badlands and mass movements (Della Seta et al. 2009). These data suggest that the indirect evaluation of *Tu* index is more reliable in fluvial basins developed in terrigenous deposits affected by landslides, with high drainage density and medium to low relief. On the other hand, the analysis of *Tu* index in limestone sub-basins showing high relief, a poorly developed fluvial net, and high stream gradients suggests a certain degree of underestimation with respect to denudation rates calculated by missing volumes. A refinement of the *Tu* experimental equations with regard to the real physiography of the studied areas is therefore desirable.

Long-term sedimentation rates have been calculated from core analysis using depth and age of tephra levels interbedded with lacustrine deposits of the San Gregorio Magno and Vallo di Diano basins. Using the ^{39}Ar/^{40}Ar age of Karner et al. (1999), the sedimentation rate in the Vallo di Diano basin during the last 0.6 Myr is 0.3 mm/yr. According to Aiello et al. (2007), a mean sedimentation rate for the last 170 kyr of 0.24 mm/yr characterizes the San Gregorio Magno basin. These values are very close to the denudation rates estimated by paleotopographic reconstruction.

Uplift rates have been calculated using the difference in height between the absolute (i.e. sea level) or local (i.e. present-day thalweg) erosion base levels and the several generations of erosional land surfaces. Vertical erosion (i.e. incision) rates have also been calculated and converted in local uplift rates assuming that eustatic changes did not produce relevant effects in this sector of the orogen. The estimation of regional uplift from the mean elevation of S1 and S2 land surfaces is based on the assumption that the morphogenesis of these morphotectonic markers occurred close to sea level (Schiattarella et al. 2009). The reconstruction of the original land surface paleomorphology based on a morphostratigraphic correlation of many remnants on a regional scale (Martino & Schiattarella 2006; Schiattarella et al. 2009) and the presence of the Pliocene marine deposits locally involved in the planation of the summit paleosurface seem to confirm this assumption.

The reconstruction of the original paleomorphology of the S3 land surfaces and the comparison with present-day longitudinal stream profiles allowed us to infer a probable fluvial origin at an elevation of about 100 m above the sea level in the sector corresponding to the present-day Auletta basin (Martino & Schiattarella 2006). This reconstruction permitted us to correct the absolute vertical movement of the S3 land surfaces and their uplift rates (Fig. 9). Regional uplift rates vary from

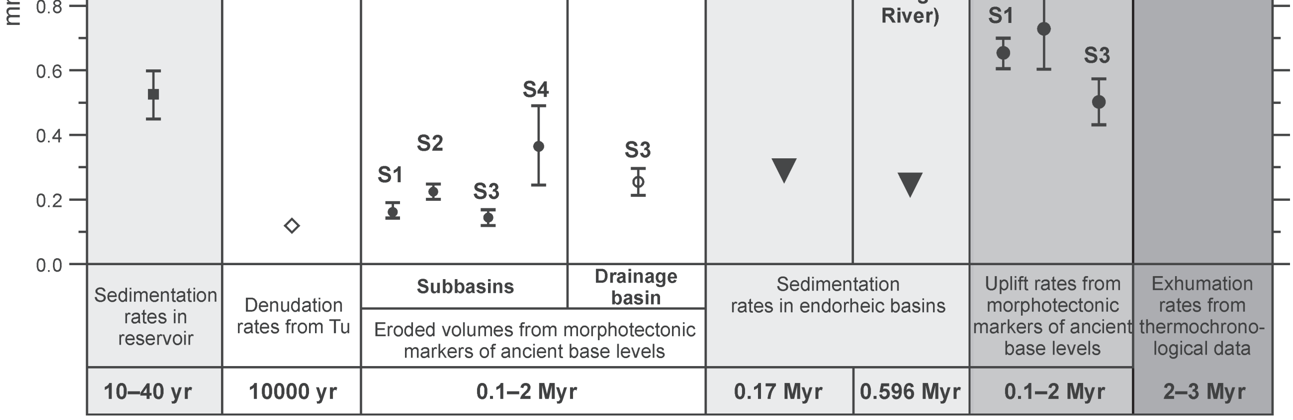


Fig. 9. Rates of denudation, sedimentation, uplift and exhumation obtained by different approaches and on multi-spatial and multi-temporal scales.

0.5 mm/yr to 0.73 mm/yr, with average values of 0.6 mm/yr. The lowest values were recorded from the S3 land surfaces (Middle Pleistocene in age) whereas the highest ones were calculated from the Lower Pleistocene relict land surfaces (i.e. the S2 erosional land surfaces).

The comparison between uplift and denudation rates suggests that the fluvial erosion did not match the tectonic uplift in this sector of the axial zone of the southern Apennines, which therefore could result a *transient landscape* (*sensu* Bracken & Wainwright 2008*)* in a non-steady system. The discrepancy between uplift and denudation rates implies two fundamental points: 1) growth of relief in the study area still occurs; 2) an increase of denudation rates during the periods of maximum uplift can be inferred (Fig. 9). Apatite fission track analysis of rocks belonging to different tectonic units of the axial zone of the southern Apennines indicates a concordant Middle to Late Pliocene final cooling age of ca. 2.5 Ma (Schiattarella et al. 2009, Fig. 9). Although the geothermal gradient is poorly constrained and the exhumation rates can be affected by errors, the values of the exhumation rates are significantly higher than estimated denudation and uplift rates. An exhumation rate of about 1.6 mm/yr for the last 3 Myr can in fact be inferred from thermochronometry, indicating the existence of past erosional processes faster than the recent and present-day exogenic dismantling, whose velocities have been obtained by our paleotopographic reconstruction. Tectonic denudation processes accounted for the exhumation of Mesozoic core of the chain during older periods (from Late Miocene to Early–Middle Pliocene) of the orogenic evolution (Schiattarella et al. 2003, 2006), but they do not seem suitable for the time interval here considered. Marine erosion linked to eustatic rising can be taken into consideration as an efficient mechanism of planation on a regional scale, able to sculpt huge flat landscapes and to dismantle large volumes of rocks. It is probable that AFT data cluster at 2.5–2.6 Myr could really represent the age of formation of the paleosurface of the southern Apennines: in such a case, the higher denudation rates may be due to the rapid dismantling of shaly units (e.g. Liguride units, i.e. ophiolite-bearing “internal” units, Sicilide units, mainly composed of deep-sea polychrome clay, and Miocene Flysch units) which tectonically or stratigraphically covered the Campania-Lucania carbonate platform.

Concluding remarks

In this work we have given an indirect estimation of the suspended sediment yield at the outlet of the drainage basin of lower valley of the Tanagro River, southern Italian Apennines, by using empirical equations between the *Tu* index and some parameters of the fluvial network (Ciccacci et al. 1980). In addition, we adopted and developed a methodology for the estimation of long-term denudation rates from the same area. Such a methodology is based on the reconstruction of the relief prior to river incision by using geomorphic markers of ancient base levels as reference surfaces. In the case of the small endorheic basin of the Pantano San Gregorio Magno, a reconstruction of the buried bedrock top was attempted in order to refine the missing rock volume estimation. Moreover, to better constrain the estimates of uplift and denudation rates, morphostratigraphical observations have been integrated with pre-existing radiometric dating (i.e. AFT analysis and Ar/Ar dating) in order to obtain a reliable definition of the ages of the morphotectonic markers.

Long-term denudation rates obtained by different approaches performed on multi-spatial and multi-temporal scales, are settled within a narrow range of about 0.1–0.2 mm/yr, in good agreement with the long-term sedimentation rates from the Vallo di Diano and the Pantano di San Gregorio Magno basins and with data on a regional scale (Amato et al 2003; Schiattarella et al. 2006, 2008). Higher values of exhumation rates from thermochronometry suggest the existence of erosional past processes faster than the recent and present-day exogenic dismantling. Other mechanisms, such as relatively rapid marine erosion of wide flatlands, can be invoked for the older stages of denudation of the southern Apennines.

Concerning the *Tu* index, it can be considered as a suitable proxy for mid- to long-term denudation rate calculations in areas characterized by fluvial processes mainly acting on terrigenous deposits with high drainage density and medium to low relief.

Quaternary uplift rates from the Auletta basin and surrounding mountains, calculated using the difference in height between the absolute (i.e. sea level) or local (i.e. present-day thalweg) erosion base levels and the several generations of erosional land surfaces, are about three times as high as the denudation rates, suggesting that the fluvial incision did not balance tectonic uplift in the area.

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