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Long-term geomorphological evolution of the axial zone of the Campania-Lucania Apennine, southern Italy: a review

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Abstract: Uplift and erosion rates have been calculated for a large sector of the Campania-Lucania Apennine and Calabrian arc, Italy, using both geomorphological observations (elevations, ages and arrangement of depositional and erosional land surfaces and other morphotectonic markers) and stratigraphical and structural data (sea-level related facies, base levels, fault kinematics, and fault offset estimations). The values of the Quaternary uplift rates of the southern Apennines vary from 0.2 mm/yr to about 1.2–1.3 mm/yr. The erosion rates from key-areas of the southern Apennines, obtained from both quantitative geomorphic analysis and missing volumes calculations, has been estimated at 0.2 mm/yr since the Middle Pleistocene. Since the Late Pleistocene erosion and uplift rates match well, the axial-zone landscape could have reached a flux steady state during that time, although it is more probable that the entire study area may be a transient landscape. Tectonic denudation phenomena — leading to the exhumation of the Mesozoic core of the chain — followed by an impressive regional planation started in the Late Pliocene have to be taken into account for a coherent explanation of the morphological evolution of southern Italy.

Keywords: Southern Apennines, uplift and erosion rates, regional morphotectonics, Quaternary landscape evolution.

Introduction

We review the results of fifteen years of scientific investigation performed by our research group in the Campania-Lucania and northern Calabria segments of the southern Apennines (Fig. 1), particularly in the axial zone of the chain where several intermontane basins filled by Pliocene and Quaternary clastic deposits are present.

Regional-scale morphostructural analysis, recognition and dating of features related to ancient base levels of erosion used as reference levels for the rates calculations, quantitative evaluation of the erosional — both fluvial and gravitative — processes, estimation of tectonic loadings suffered by the sedimentary rocks that form the backbone of the southern Apennines and the consequent estimate of the exhumation rate of the non-metamorphic "core complex" of the chain, recognition and recording in a wide area of palaeoclimate proxies, such as palaeosols, weathering horizons, planation surfaces, and palaeolandslides, allowed us to obtain a detailed and synoptic picture of the landscape evolution of the chain during the last 3 Ma.

Geological and geomorphological framework

The southern Apennines are a northeast-verging fold-and-thrust belt mainly composed of shallow-water and deep-sea sedimentary covers (Fig. 1), deriving from Mesozoic–Cenozoic circum-Tethyan domains (Patacca & Scandone 2007), covered by Neogene–Pleistocene foredeep and satellite-basin deposits (Pescatore et al. 1999). The hinge of the subducting plate of the orogenic system coincides with the present-day eastern foreland area (carbonate Apulian platform, Fig. 1).

Starting from the Tortonian, the orogen underwent low-angle extension which led to the exhumation of its non-metamorphic core complex constituted of Mesozoic Lagonegro-type pelagic units (Schiattarella et al. 2003, 2006, and references therein).

This regional framework has been strongly complicated by Quaternary tectonics, responsible for the formation of longitudinal and transversal fault-bounded basins (Aucelli et al. 2014), for the displacement of several generations of planation surfaces (Amato & Cinque 1999; Schiattarella et al. 2003, 2013), and for the re-organization and control of many hydrographic networks (Beneduce et al. 2004; Capolongo et al. 2005). Southern Italy underwent significant uplift during the Quaternary, with average rates 0.6–1 mm/yr (Westaway 1993; Schiattarella et al. 2003).

The southern Apennines are characterized by an asymmetrical topographic profile (Fig. 2a). The summit line of the mountain belt is markedly shifted westward and does not correspond to the regional water divide (Fig. 2b). Consequently, the eastern flank of the chain has a greater length and a lower mean gradient than the western flank. Swath profile (Fig. 2c) highlights

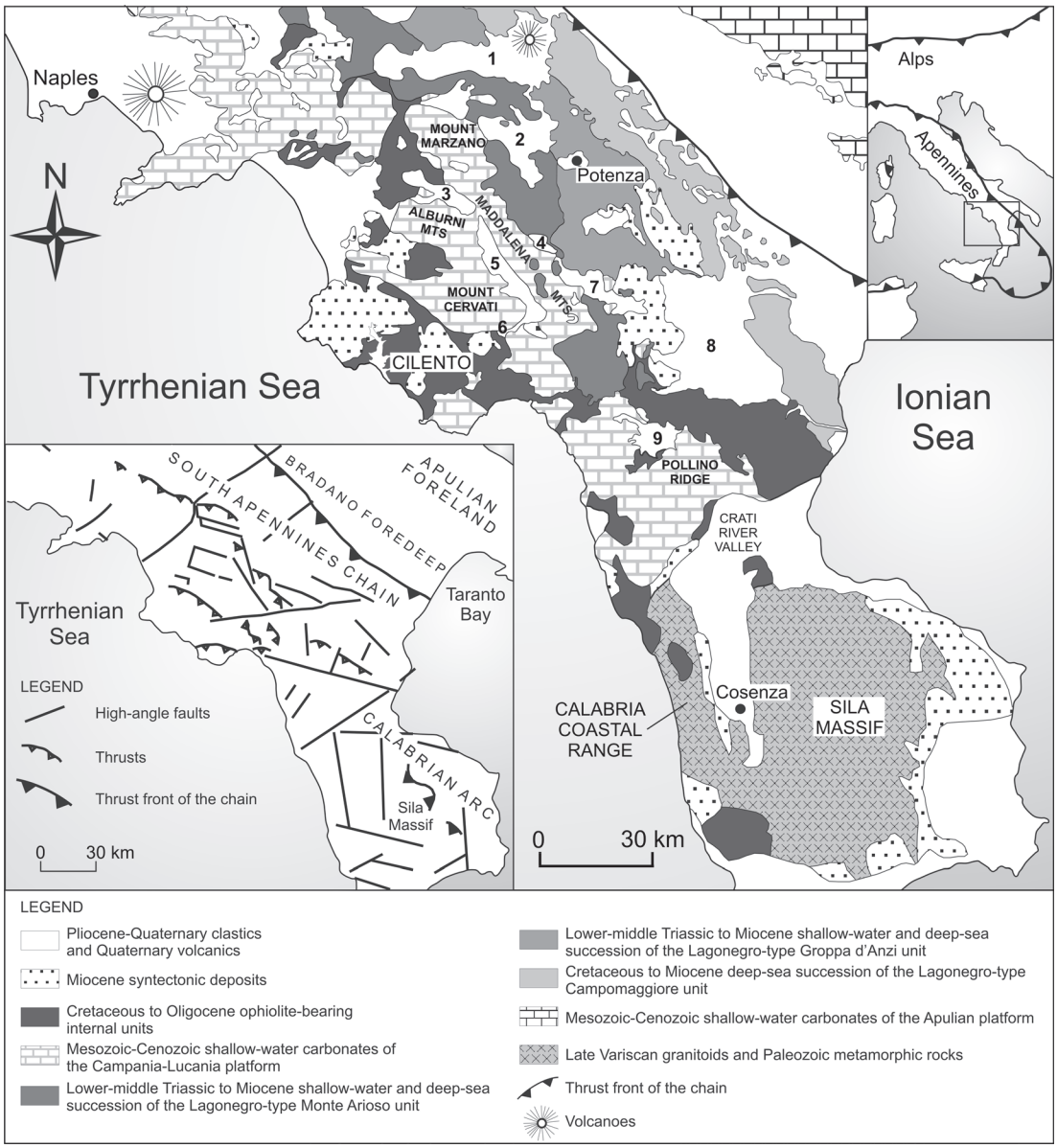

Fig. 1. Geological sketch map of the Campania-Lucania Apennine and northern Calabria. In the frame, main tectonic structures are reported. Toponyms of the intermontane basins (indicated with numbers): 1. Ofanto basin; 2. Tito-Picerno basin; 3. Auletta basin; 4. Pergola-Melandro basin; 5. Vallo di Diano basin; 6. Sanza basin; 7. Agri basin; 8. Sant'Arcangelo basin; 9. Mercure basin.

a regional and asymmetrical topographic bulge, with its culmination roughly coinciding with the axial zone of the chain. In this sector, we can also discriminate a shorter wavelength topographic signal, which is related to the basin-border fault activity. Higher uplift rates of the axial sector of the southern Apennines can reasonably be attributed to the coupled forces of regional raising and local fault activity.

The tops of the mountain belt of the axial zone of the chain can exceed the altitude of 2000 m a.s.l. and are frequently characterized by a low angle topography representing remnants of an ancient flat landscape, uplifted and dismembered by Quaternary fault activity. Consequently, these palaeosurfaces are arranged in several superimposed levels (Schiattarella et al. 2003, 2006, 2013; Boenzi et al. 2004; Putignano & Schiattarella 2008; Di Leo et al. 2009; Martino et al. 2009; Amato et al. 2011; Gioia et al. 2011b; Robustelli et al. 2014; Giano 2016).

The landscape of the Campania-Lucania Apennine was strongly controlled by tectonics. The fault slopes of many ranges and adjacent intermontane basins are often the surface expression of the Pliocene to Quaternary block faulting (fault scarps and fault line scarps bound in fact many mountain fronts, cf. Brancaccio et al. 1978, and Giano & Schiattarella 2014), and the drainage networks are frequently controlled by fracture systems (Capolongo et al. 2005). The more destructive and strong earthquakes of the region are located along

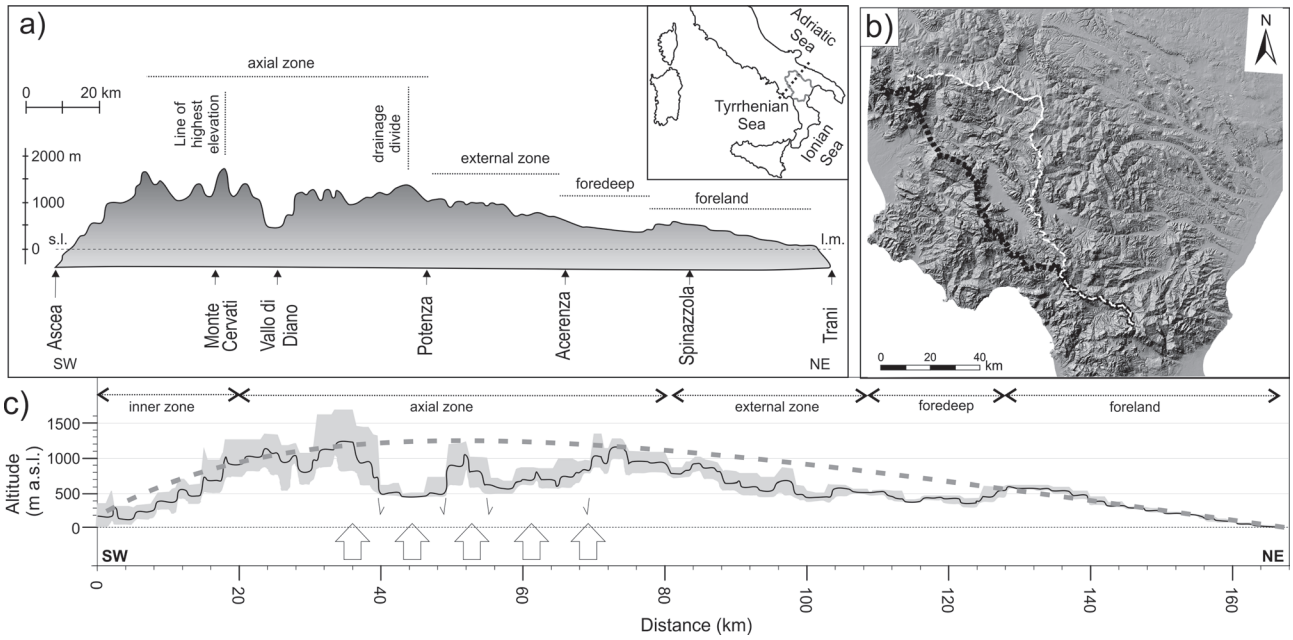

Fig. 2. a — Topographic profile of southern Italy, from Tyrrhenian to Adriatic coastlines; **b** — shaded relief of part of the Campania, Basilicata, and Calabria Apennines with regional watershed (white dashed line) and maximum elevation line (black dotted line); **c** — swath profiles (swath width of 2 km, profile trace in the sketch map) from the southern Apennines. Arrows indicate the sector of the chain featured by higher uplift rates and by main basin-border high-angle faults, whereas the dashed grey-line marks the asymmetrical topographic bulge of the mean topography.

the NW–SE and NE–SW-trending high-angle faults, sometimes with clear geomorphic expression. Some palaeosols were involved in Late Quaternary faulting, furnishing C^{14} ages included between 40,000 and 8000 years B.P. (Giano et al. 2000; Moro et al. 2007; Giano & Schiattarella 2014).

Northern Calabria, which from a geographical point of view represents the southern continuation of the Apennines, is made up of crystalline metamorphic units thrust on the Mesozoic African-Apulian carbonate domains, locally outcropping in tectonic windows. It is part of the larger Calabrian arc and is also characterized by flat-topped mountains, especially in the Sila Massif, where the top palaeolandscapes are deeply affected by tropical-type weathering and show tens-of-metres-thick regolith and/or altered rock horizons (Guzzetta 1974; Scarciglia 2015).

Morphotectonics

A relevant number of morphostratigraphic profiles across the intermontane basins and contiguous mountain ranges of the axial zone of the southern Apennines (examples in Fig. 3) have been realized analysing both the arrangement of relicts of planation surfaces scattered at different elevations a.s.l. and other key morphostructural markers, such as truncated karst landforms, fault-related slopes, and hanging valleys (Schiattarella et al. 2003, 2006; Boenzi et al. 2004; Gioia & Schiattarella 2010; Di Leo et al. 2009, 2011; Martino & Schiattarella 2010; Gioia et al. 2011b; Giano 2011; Giano & Giannandrea 2014; Giano & Schiattarella 2014; Giano et al. 2014b).

The signatures of the continental base-level changes during the last 2–3 Ma have been adequately preserved in both the geological and geomorphological features of the intermontane basins, such as flat land surfaces and tops of alluvial deposits.

The exhumation of the core of the chain occurred since the late Miocene by low-angle extension, followed by erosional processes on a regional scale that led to the formation of the summit palaeosurface. An earlier event at 9.2 Ma and two different clusters included in the 5.5–5.0 and 3.9–1.5 Ma ranges in the distribution of the apatite fission-track data (Fig. 4) can be attributed to two previous stages of tectonic denudation followed by a relatively fast planation (Schiattarella et al. 2013). It means that the erosion processes leading to the formation of such a morphological feature was promoted by the incipient rising of the chain, but their rates were faster than the uplift ones. It is possible that the regional palaeosurface was formed at the sea level by marine erosion, and subsequently moulded by fluvial and karst processes, so assuming the character of a polygenetic landform (Amato & Cinque 1999; Martino & Schiattarella 2006).

In the different catchment basins and surrounding ranges, three or four generations of erosional land surfaces, carved in both Mesozoic–Cenozoic bedrock and Pliocene–Quaternary clastic sediments of the basin infill, are normally recognized (Schiattarella et al. 2003; Boenzi et al. 2004; Gioia et al. 2011b; Giano 2016). The highest land surface (summit palaeosurface, or S1 after Schiattarella et al. 2003) represents

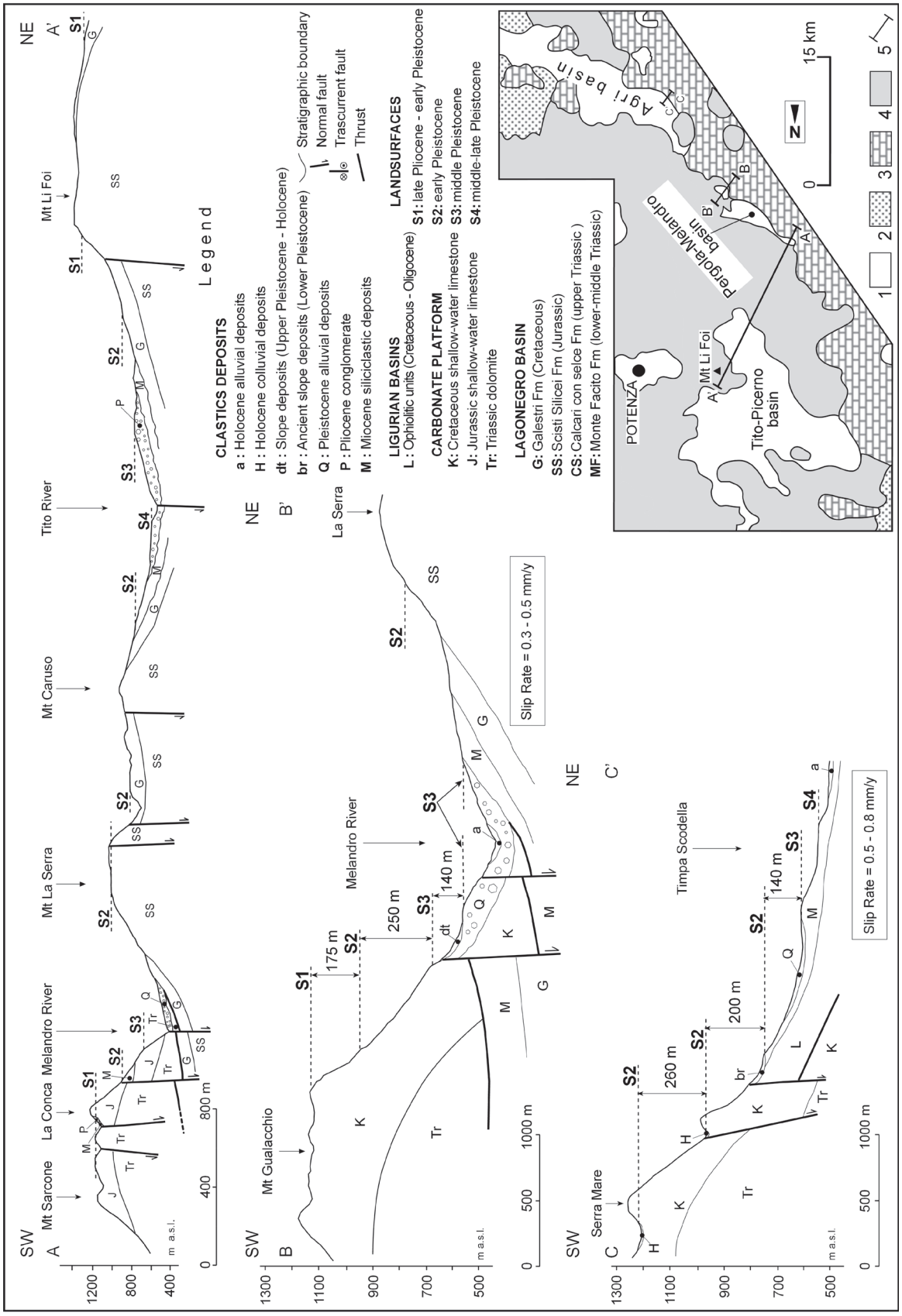

Fig. 3. Morphostratigraphic profile (A–A') from the axial zone of the Lucanian Apennines and detailed morphostratigraphic sections (vertical exaggeration 2×) from Melandro (B–B') and Agri (C–C') valleys, adopted for slip rate calculation. Note that the slip rates refer to different time spans (from 1.8 to 1.2 Ma and from 1.2 to 0.8–0.7 Ma for B–B' and C–C' profiles, respectively). In the frame, location of the profiles is reported on a simplified geological scheme (1. Pliocene to Quaternary clastics; 2. Miocene siliciclastic deposits; 3. Mesozoic–Cenozoic shallow-water carbonates; 4. Mesozoic–Cenozoic deep-sea Lagonegro units; 5. Trace of section). Modified after Schiattarella et al. (2003).

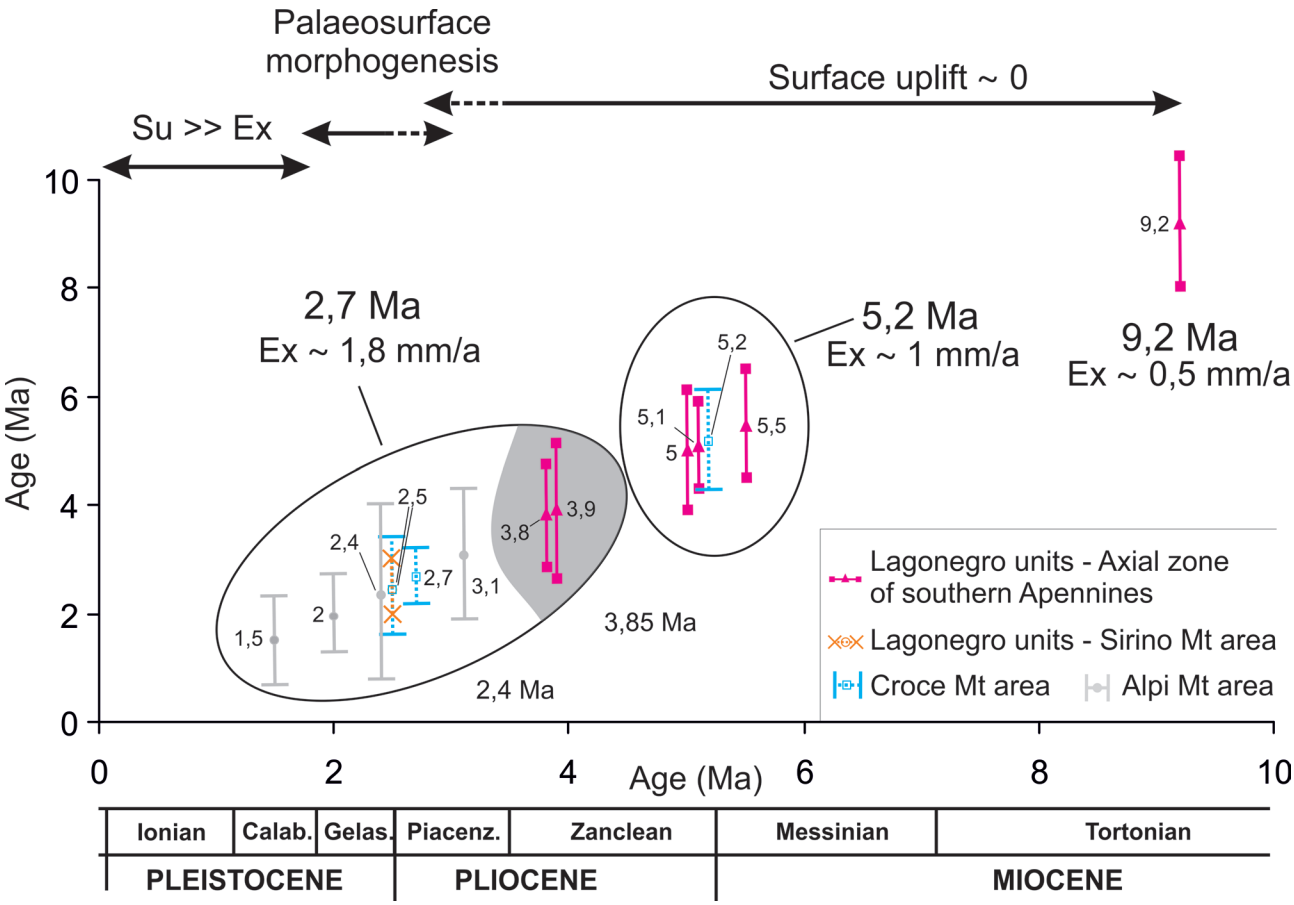

Fig. 4. AFT ages from the southern Apennines (after Aldega et al. 2005, Schiattarella et al. 2006; Mazzoli et al. 2008; Schiattarella et al. 2013). The younger cluster groups cooling ages included in the 2.4–2.7 Ma range (in turn comprised in the wider 3.9–1.5 Ma set) and represents the exhumation episode linked to the relatively fast planation of the chain during the Pliocene-Pleistocene transition, whereas the older clusters (at about 5 and 9 Ma) have to be attributed to tectonic denudation phenomena (i.e. low-angle extension) leading to the genesis of the non-metamorphic "core complex" of the southern Apennines (Schiattarella et al. 2003, 2006; Invernizzi et al. 2008; Mazzoli et al. 2008). Note that, according to such an interpretation, the final stage of unroofing was not accompanied by a relevant footwall uplift of the core complex, favouring the formation of the regional palaeosurface.

the morphological remnants of a regional planated landscape. They unconformably cut across tilted Mesozoic–Cenozoic shallow-water limestones, coeval basinal formations and Lower–Middle Pliocene marine sediments outcropping along the Campania-Lucania segment of the southern Apennines.

Relative and absolute dating of the summit palaeosurface indicated that it developed in the Late Pliocene, but the planation process was still active during the Early Pleistocene (Gioia et al. 2011a; Schiattarella et al. 2013). The morphological de-activation of a land surface is achieved when it undergoes to a significant tectonic hanging and acquires the condition of relict landform. In this way, fault-controlled basins are often surrounded by flat-topped ridges.

Because of the Late Pliocene age of the oldest palaeosurface (S1 after Schiattarella et al. 2003) generally found above 1100 m a.s.l., the lower S2 erosional land surfaces (often at about 900–1000 m a.s.l.) has to be attributed to the Early Pleistocene (Schiattarella et al. 2003). This is also proved by the presence of Early Pleistocene fluvial deposits in many basins of the axial zone (Aucelli et al. 2014), morphologically inserted in such flat surfaces. The S2 surfaces frequently represent dislocated remnants of the oldest one (S1), subsequently re-moulded by processes acting in a continental environment.

The S3 erosional surfaces have been used to morpho-stratigraphically correlate the clastic infill of the different basins (Schiattarella et al. 2003; Boenzi et al. 2004); as a matter of fact, the S3 land surfaces often cut both bedrock and Pleistocene fluvio-lacustrine deposits along the axis of the entire Campania-Lucania orogenic segment. Several key-data about the ^{40}Ar–^{39}Ar ages of tephra layers interbedded in the fluvial-lacustrine deposits of Vallo di Diano and Sanza basins (Karner et al. 1999; Di Leo et al. 2009; Giano et al. 2014a,b) allowed us to closely constrain the genesis and de-activation of the S3 surfaces that can be reasonably referred to the Early Pleistocene–Middle Pleistocene time span.

The tectonic loadings suffered by the rocks of the non-metamorphic "core complex" cropping out in the southern Apennines have been estimated to be not less than 4–5 km

(Schiattarella et al. 2003, 2006; Aldega et al. 2005). Mechanisms of tectonic denudation have therefore been invoked by several authors to reach the present-day configuration of the chain (Schiattarella et al. 2003, 2006; Corrado et al. 2005; Mazzoli et al. 2008).

The thermal history of the different tectonic units of the southern Apennines (Aldega et al. 2005) has been studied by Apatite fission-track analysis (Fig. 4). Such data, combined with geological and morphotectonic results, furnished a picture of the exhumation of the rocks from the uppermost part of the crust (i.e. above the 110°C isotherm). On this basis, we infer that the planation surface sculpture, occurred in a relatively short time span of low-rate tectonic activity (more or less 1 Ma), is the geomorphic expression of the above episode of exhumation (i.e. the erosion/planation rate exceeds the rock uplift rate). This is also demonstrated by the presence of many marine to continental basins filled by thick successions of Pliocene clastic rocks (locally involved in the planation processes) deriving from the dismantling of a previous, namely Upper Miocene–Lower Pliocene relief.

As above reported, 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, Gioia et al. 2011a; Schiattarella et al. 2013), suggesting a widespread exhumation during the Late Pliocene. Since apatite passed the closure temperature isotherm at about 2.5 Ma, a considerable (~2 km) exhumation/denudation was needed to reach the surface. Therefore, the planation process was probably still active during the Early Pleistocene.

This relatively young exhumation is likely 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 erosional processes. It can be argued that such a regional shaping could be related to the summit palaeosurface morphogenesis. The attribution of those features to the Late Pliocene is strengthened by the presence of Lower–Middle Pliocene clastic deposits outcropping at the top of the Maddalena Mts (Schiattarella et al. 2003) and in the Mt. Marzano area (Fig. 1), involved in the planation of the palaeosurface, which means that the Pliocene sediments are truncated by the erosional sub-horizontal surface.

The transition period between the Late Pliocene and the Early Pleistocene represents the time span in which the summit palaeosurface developed, when the decreasing rates related to tectonics were efficiently faced by the climate-induced erosional processes (i.e. triggered by the global cooling that started about 3 Ma). In such a way, the exhumation of deep rocks was accompanied by the progressive planation of a slowly uplifting chain, meaning that the antiformal stack was constantly truncated during its emersion, so permitting the creation of a regional-scale flat landscape. This feature, formed at the sea level by marine erosion and then moulded by fluvial and karst processes (Amato & Cinque 1999; Martino & Schiattarella 2006), was partly displaced by the 2.5 Ma tectonic stage in the Tyrrhenian flank of the Pliocene wedge (today submerged) and more largely fragmented by the 1.8 Ma tectonic stage in the spatial domain of the present-day chain. Its displacement and fragmentation created a younger generation of polygenetic land surfaces, in turn faulted and hung with regard to the erosion base level at about 1.2 Ma ("Emilian" tectonic stage).

Uplift and erosion rates

The tectonic stages between 2.5 and 0.125 Ma in the axial zone of the chain were responsible for both the displacement of the planation surfaces and the subsidence of the Upper Pliocene to Quaternary basins (Brancaccio et al. 1991; Amato & Cinque 1999; Schiattarella et al. 2003; Gioia et al. 2011a; Giannandrea et al. 2014).

Morphotectonic data indicating gently dipping, horizontal, or slightly undulated land surfaces, fault slopes and fault scarps, plano-altimetric offset of minor divides, fault-controlled streams, hanging valleys, wine-glass shaped valleys and so on, have been obtained all along the axial zone of the chain, from the northernmost mountains of the southern Apennines to the Calabrian Arc (Schiattarella et al. 2006, 2013). The attribution of a relative age to each planation surface generation, based on well-defined deactivation stages of the same land surfaces by Quaternary tectonics, allowed us to reconstruct the morpho-evolutionary stages of the southern Apennines since the Late Pliocene and to calculate the values of the regional and local tectonic uplift of a large sector of the chain.

The estimated regional and local uplift rates have improved our comprehension of the possible dynamic state of the south-Apennine orogenic system (Schiattarella et al. 2006). The regional uplift rates have been calculated on the basis of the elevation of reference surfaces with regard to the absolute (or ultimate) base level (i.e. the present-day sea level), whereas the local uplift rates have been estimated using the same morphological elements with regard to local base levels such as alluvial floodplains or lacustrine basins. In detail, a clear decrease of the local uplift rates took place between 1.2 and 0.7 Ma whilst increasing rates characterize the Middle Pleistocene (Fig. 5).

If we examine the whole south-Apennine chain, a quasi-linear trend of growth of the regional uplift since the end of the Pliocene can be deduced (Fig. 5). However, a differential behaviour of two adjacent sub-regional sectors has to be taken into account for the comprehension of the long-term uplift history, since the Alburni Mts.–Mt. Marzano area is characterized by a flat uplift rate curve. Therefore, we may hypothesize a further subdivision of the axial zone due to the existence of a significant kinematic release between the most internal (i.e. Cilento) belt and the most external one (axial zone *s.s.*).

Several morphometric profiles with geological information intercepting basin border faults (Fig. 3) of the Agri and the Pergola-Melandro valleys (Schiattarella et al. 2003, 2006;

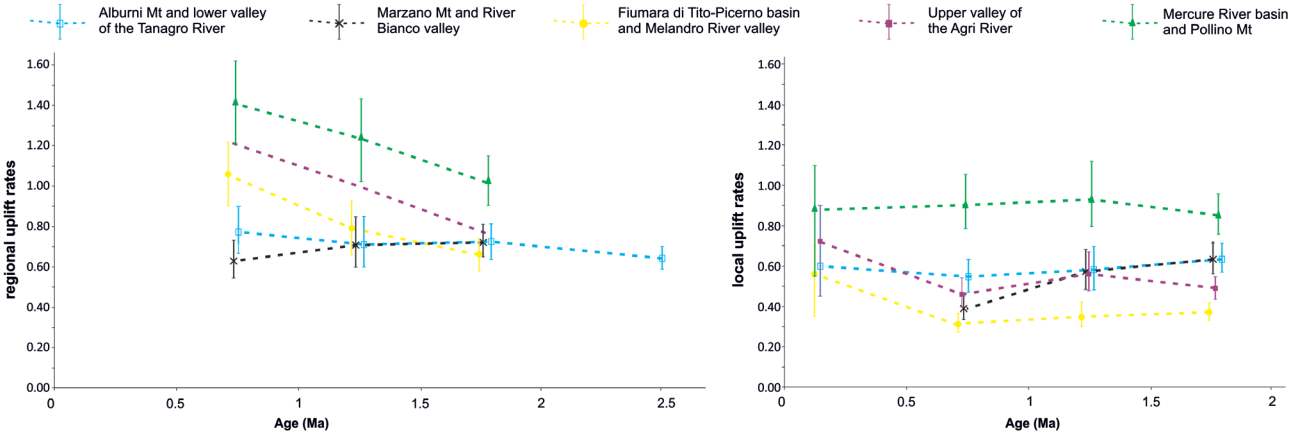

Fig. 5. Diagrams showing the variation of the regional and local uplift rates from five key-areas of the axial zone of the southern Apennines during the Quaternary.

Boenzi et al. 2004; Giano & Schiattarella 2014), and the morphostratigraphic correlations from the Vallo di Diano and Sanza basins based on recent ^{40}Ar–^{39}Ar dating of tephra layers (Di Leo et al. 2009; Giano et al. 2014a,b) allowed us to compute the slip rate values of the faults and to compare them to the local uplift values. The last kinematics of such faults is expressed by normal slip and was responsible for major Quaternary offsets and basin widening during Middle to Late Pleistocene times (Giano et al. 2000). Former strike-slip faulting which affected the whole south-Apennine chain starting from the Late Pliocene (Schiattarella 1998), with horizontal offsets of few kilometres as a maximum, did not favour the relief growth like that generated during Middle–Late Pleistocene times. This is also documented by low rates of a normal component of faulting during the Late Pliocene–Early Pleistocene. In fact, the fault-slip rates (referred to the vertical component of motion, cf. Boulton & Whittaker 2009) from the upper Agri Valley and Pergola-Melandro basin vary from 0.3 to 0.5 mm/yr in the time interval included between 1.8–1.2 Ma, and from 0.5 to 0.8 mm/yr in the 1.2–0.7 Ma time span (Schiattarella et al. 2003; Boenzi et al. 2004). The 0.3–0.5 mm/yr slip rate value has also been obtained for the Vallo di Diano basin fault system, but in relation to the activity started from the Early–Middle Pleistocene boundary (Giano et al. 2014a,b). Therefore, it can be argued that the Monti della Maddalena carbonate ridge, separating the Pergola-Melandro and Agri basins from the Vallo di Diano basin, is bounded on its western side by a master fault with a constant slip rate, whereas on its eastern slopes is bordered by a fault system whose displacement rate progressively increased (see locations of the cited sites in Fig. 1).

The comparison between the uplift and erosion rates of the whole south-Apennine chain allowed us to recognize the dynamic state of the orogen (*sensu* Willett & Brandon 2002). The quantitative geomorphic analysis has been used for the computation of the linear erosion and the estimation of the missing volume of sediment in many fluvial catchments (Schiattarella et al. 2004, 2006, 2008). Several indices have been calculated for quite different drainage basins. Some of them may have a morphotectonic meaning, whereas others are needed for erosion estimates (Strahler 1957). Bifurcation ratio and index (*Rb*, *Rbd*, and *R*) express the state of hierarchical organization of the drainage network, which is related to the maturity of the basin and to its geomorphological processes. Hierarchic anomaly number and index (*Ga*, *Da*, and *ga*, after Avena et al. 1967) and the morphometric estimation of suspended sediment yield (*Tu* [t/km^2/year], after Ciccacci et al. 1980) represent an expression of the strength of the fluvial erosion (Della Seta et al. 2007).

Such an analysis permitted us to suppose the existence of a linear correlation between the suspended sediment yield (*Tu*) and the missing volume of sediment in the drainage basins (V in Fig. 6) thus supplying a tool for the evaluation of the erosion rate. Short-term denudation rates have been calculated converting the parameter *Tu*, derived from the quantitative geomorphic analysis, in the parameter *Ta* (expressed in mm/yr), obtained considering the average density of outcropping rocks of sample areas according to the following expression:

$$Ta = Tu/\gamma s * 10^{-3}$$

where *Tu* is the suspended sediment yield and γs is the specific weight of the drained rocks.

Mid- to long-term denudation rates have been obtained from the calculation of eroded volumes of rocks with regard to reference levels such as fluvial terraces and palaeosurfaces, or from the estimation of bedrock incision rates (Burbank & Anderson 2001). Refinements of the rate values have been achieved by comparisons between long- and short-term erosion rates, so obtaining an average value of about 0.2 mm/yr in the Middle Pleistocene to Holocene range (Fig.7).

The average values of the Quaternary regional uplift rates of the south Apennines axial zone are equal to 0.6–0.7 mm/yr, with peaks of ~1.2–1.3 mm/yr in the Agri Valley and Pollino Ridge (see location of these sites in Fig. 1 and rate values in

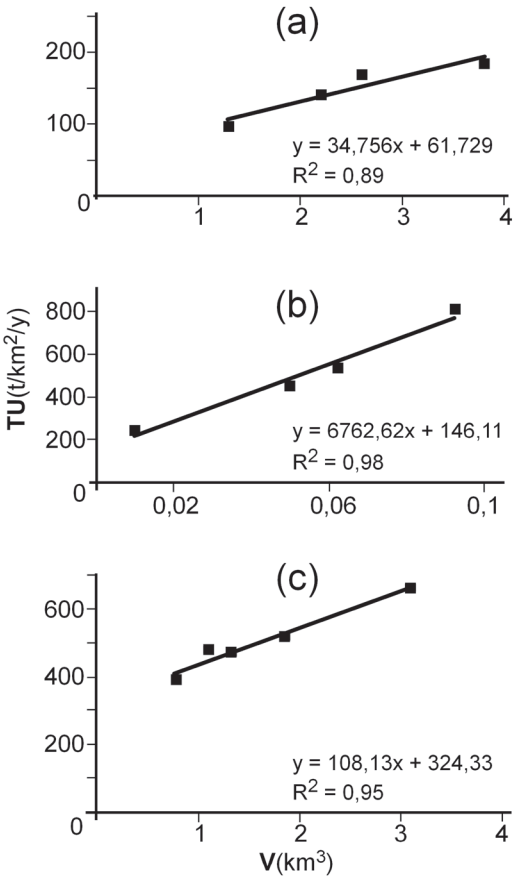

Fig. 6. Relationships between the suspended sediment yield (Tu) and the eroded volumes (V) calculated for the fluvial sub-basins of the **a)** Auletta basin (i.e. Tanagro River lower valley), **b)** Melandro River catchment, and **c)** Fiumara di Tito-Picerno catchment.

Fig. 5). An increasing trend of uplift rate toward the south can be observed. An acceleration of the local component of vertical motion starting from the beginnings of the Middle Pleistocene and slowing of the uplift rates during the Late Pleistocene down to 0.2 mm/yr can be deduced as well (Boenzi et al. 2004; Giano & Schiattarella 2014).

Since erosion and uplift rates match well in the Late Pleistocene, the axial zone landscape could have reached a flux steady state (Willett & Brandon 2002) just in that stage. This is also suggested by low values of fault slip rate, as in the case of the fault-bounded upper Agri Valley and Pergola-Melandro basin — among the most active seismic zones of Italy — in which during the last 30 ky, the main high-angle faults were characterized by a slip rate decreasing to about 0.1 mm/yr (data from Giano et al. 2000).

Nevertheless, it is worth noting that the ratio between uplift and erosion rates related to Quaternary long-term landscape evolution of the chain is about 3:1. Further, in the Middle Pleistocene to Holocene time span, low values of denudation rates (i.e. about 0.1 mm/yr) have recently been recognized in the northern sector of the Pliocene–Pleistocene foredeep of the southern Apennines on the basis of fluvial terrace chronostratigraphy, supported by OSL and AAR dating (Gioia et al. 2014). In this sector, Middle to Late Pleistocene uplift rates from the elevation of marine terraces are quite similar to the denudation rates, thus suggesting a near steady-state landscape.

Such a space-time pattern suggests that the Late Quaternary steady state could represent only a fluctuation of a more general transient state of the orogenic segment here studied.

Final remarks

The data acquired of the last fifteen years has made possible to discriminate between the amount of the regional uplift and the local uplift generated by master faults of basins that together have produced the present day elevation a.s.l. of the ancient planation surfaces. In some axial-zone basins (such as the Melandro River basin) a comparable partitioning between local (i.e. induced by faulting) and regional (tectonic) uplift was responsible for the present elevation of the relict land surfaces, whereas the relief of the Agri River upper valley can be almost totally ascribed to the activity of basin-border faults. Higher uplift rates, recorded in the Mercure basin-Pollino Ridge area and in the Calabria Coastal Range (Fig. 1), indicate a southward increasing trend of the uplift rate related to the stronger activity of the high-angle faults. During the Quaternary, the total amount of tectonic uplift of the axial zone of the southern Apennines is ~1.2–1.3 km, with local peaks of 1.5 km (Schiattarella et al. 2006). The most relief of the chain was gained starting from the Middle Pleistocene, when normal faulting became the major deformational mechanism.

Tectonic loadings suffered by the Mesozoic deep-sea rocks of the southern Apennines have been estimated to be not less than 4–5 km (Schiattarella et al. 2003, 2006; Aldega et al. 2005), or greater for the area of the Calabria-Lucania boundary (Di Leo et al. 2005; Invernizzi et al. 2008). The considerable difference (about 3 km) between the relief gain and the lost overburden needs an alternative explanation with regard to the ordinary erosion processes (i.e. not exclusively linked to the uplift-erosion interplay). Assuming a fixed uplift rate of 0.6 mm/yr to reach a response of ~4–5 km in denudation (i.e. rock uplift), a Tortonian (Late Miocene) exhumation age can be obtained. This age is concordant with the older exhumation age furnished by apatite fission-track analysis (Aldega et al. 2005). Tectonic exhumation ("tectonic erosion" *sensu* Mancktelow 2000; see also "tectonic denudation" in Ring et al. 1999 and in Burbank and Anderson 2001) may be a reliable explanation for the above mentioned gap (i.e. between the amounts of rock uplift and surface uplift, *sensu* England and Molnar 1990). Low-angle extensional faulting may be taken into account as the dominant mechanism of such an evolution, responsible for both the exhumation of the Mesozoic core of the chain (Lagonegro units) and the reactivation and inversion of older thrusts on its Tyrrhenian side, whereas gravitative stacking represents the counterpart of those phenomena on the frontal sector of the orogen (Schiattarella et al. 2006).

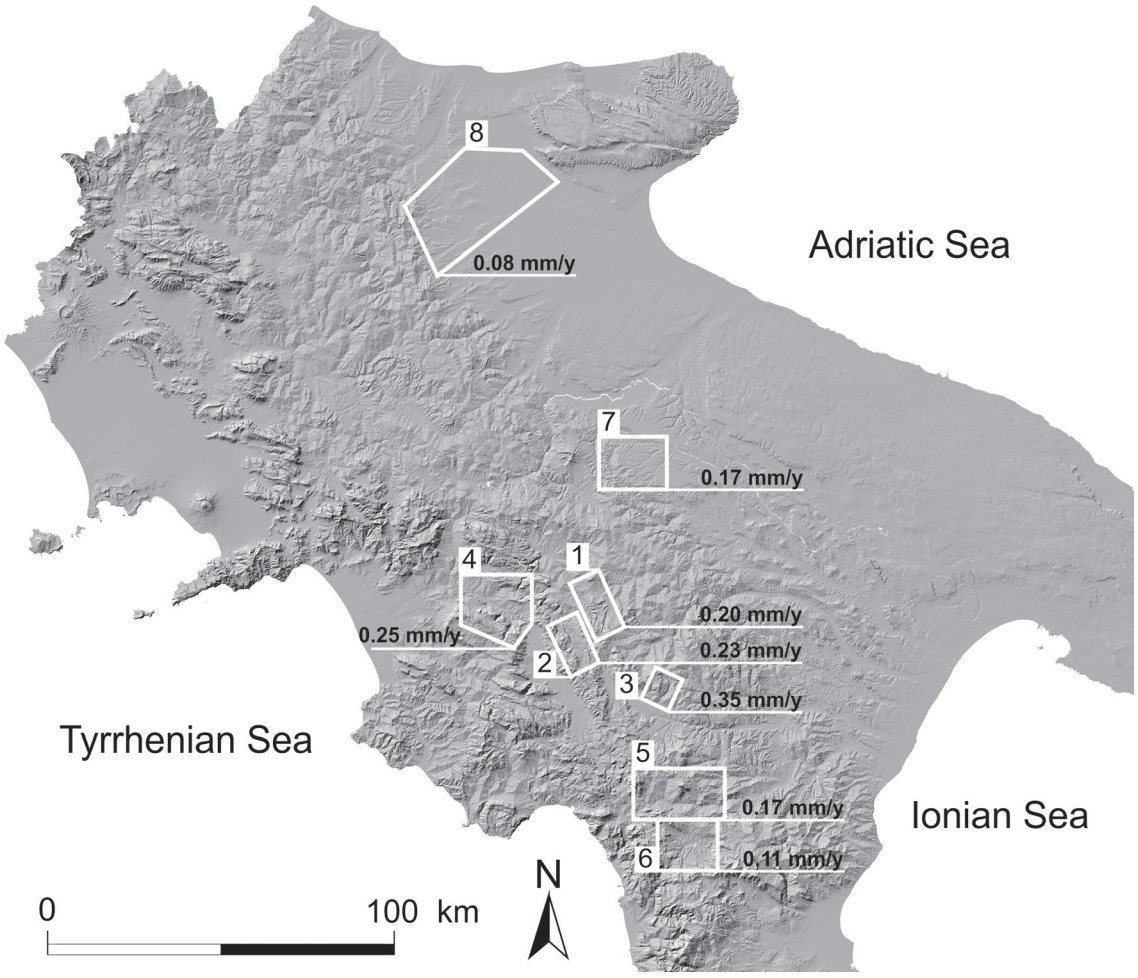

Fig. 7. Location of the study areas in southern Italy and related values of erosion rates. Toponyms: 1) Fiumara di Tito-Picerno basin; 2) Melandro River Valley; 3) Agri River Upper Valley; 4) Tanagro River Lower Valley (i.e. Auletta basin); 5) Sinni River Upper Valley; 6) Mercure River basin; 7) Fiumara di Venosa basin; 8) Tavoliere di Puglia plain (modified after Schiattarella et al. 2008).

The orogen derived from the fold-and-thrust tectonics and subsequent exhumation processes was largely modelled as a long-wavelength or flat landascape from the Late Pliocene, as suggested by both the more recent cluster of AFT (Fig. 4) and field data. The chain was subsequently cut off by transcurrent and normal high-angle faults responsible for its recent uplift in combination with several regional mechanisms, such as deep stacking of crustal elements in the axial portion of the chain and footwall uplift of its western sector by back-arc extension (Schiattarella et al. 2006, 2013).

Since the long-term fluvial erosion did not match the tectonic uplift of the axial zone of the southern Apennines, this region has been largely hit by other erosion phenomena. Above all, mass movements are needed to drop the disequilibrium triggered by rates differential (Schiattarella et al. 2008; Lazzari & Schiattarella 2010; Santangelo et al. 2013).

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