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Quaternary uplift vs tectonic loading: a case study from the Lucanian Apennine, southern Italy

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Abstract

Uplift rates have been calculated for a large sector of the Lucanian Apennine ("axial zone" of the southern Apennines, Italy), using both geomorphological observations (elevation values, ages and arrangement of depositional and erosional landsurfaces and other morpho-tectonic indicators) and stratigraphical and structural data (sea-level-related facies, fault kinematics and offset estimations). These data have been compared with those derived from clay mineralogy of Mesozoic pelagic successions (*Lagonegro units*), outcropping in the same sector of the chain, which gave information on tectonic loading.

The values of the Quaternary uplift rates of the southern Apennines axial zone vary from a minimum of 0.2 mm/yr to a maximum of about 1.2 mm/yr. Intermediate values (0.5–0.7 mm/yr) have been calculated for the other studied areas. Using geomorphological features and late Pliocene to Pleistocene successions involved in the genesis of erosional and depositional landsurfaces, the same rates ($\sim$0.6 mm/yr) have been obtained for a large time span (about 2 Ma) in the Melandro basin and adjacent Maddalena Mts. Therefore, during the last 2 Ma, the total uplift amount of the axial zone of the Lucanian Apennine is about 1.2–1.3 km, with local peaks of 1.5 km. On the other hand, the Mesozoic pelagic units experienced a tectonic loading of 4–5 km, as estimated by means of illite crystallinity (in the range 0.6–1.1 $\Delta°2\theta$), percentage of illitic layers in illite/smectite mixed layers (60–90%) and white mica polytypes (in the range of 10–35%).

The Quaternary uplift and the related erosion rates of the southern Apennines are unquestionably due to strike-slip faulting and, above all, due to extensional tectonics coupled with thermal/isostatic regional raising. The gap of several kilometres derived from the comparison between uplift rates and tectonic loading values may be explained only by different exhumation modalities starting from late Miocene time.

1. Introduction

In many young chains of the Alpine orogenic cycle, Quaternary tectonics and regional uplift are traditionally considered strictly correlated and almost synonyms. Actually, few data are available for precise calculations of uplift rates for different Mediterranean regions, although such quantitative studies are needed to define the relationships between local faulting and large-scale uplift due to thermal raising or isostatic compensation, lithosphere delamination or lithospheric thinning and necking, lithospheric flexure, footwall uplift, crustal doubling or sub-crustal accretion, slab detachment and consequent rebound of the subduction hinge. In addition, data about burial depths of sediments or tectonic loading suffered by sedimentary and low-grade metamorphic rocks are also welcome for comparisons with the uplift rates obtained in the same areas. Such comparisons between quite different data sources improve the comprehension and choice of the most reliable mechanism responsible for the regional uplift.

In this paper, uplift and/or erosion rates have been calculated for a large sector of the Lucanian Apennine (southern Apennines, Italy), using geomorphological (elevation values, ages and arrangement of depositional and erosional gently dipping landsurfaces and other morphotectonic indicators), stratigraphical (sea-level-related facies and marker beds), and structural (fault kinematics and offset estimations) data. The sector investigated covers the "axial zone" of the chain (Ortolani et al., 1992) and includes the Agri River high valley, the Melandro River basin and surrounding

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elevated areas, the Pignola Quaternary basin, the Mt Li Foi area and Tito-Picerno basin, and the Potenza Pliocene piggy-back basin.

These data have been compared with those derived from analysis of Mesozoic pelagic successions (*Lagonegro units*), which gave information on tectonic loading by means of geothermometers based on clay minerals. Triassic to Cretaceous successions outcropping in the Lucanian Apennines were analysed. The *Monte Facito*, *Calcari con selce*, *Scisti silicei* and *Galestri* formations were chosen because of their regional extent and the high frequency in these successions of pelitic layers rich in clay minerals. Analysis of this composite data set allowed inferences concerning geomorphological and geodynamic suggestions about the maximum Quaternary uplift and the exhumation age of the successions outcropping along the south-Apennines axial zone.

2. Geological and geomorphological setting

The southern Apennines are a northeast-verging fold-and-thrust belt (Fig. 1), built on the western border of the Apulian plate from late Oligocene–early Miocene times (Pescatore et al., 1999). The belt is mainly composed of shallow-water and deep-sea sedimentary covers, derived from Meso-Cenozoic circum-Tethian domains and from the Neogene–Pleistocene foredeep deposits. The Apulian palaeomargin included the Lagonegro basin, which was generated by middle Triassic continental rifting (Scandone, 1975). From Langhian–Tortonian times, the thrust front moved progressively toward the east, as documented by the age and meaning of syntectonic deposits (Pescatore et al., 1999). Contractional tectonics continued until early middle Pleistocene in the external zone, as indicated in some frontal sectors of the chain (Pieri et al., 1997). A conservative shortening up to 200 km has been calculated for the orogenic wedge (Schiattarella et al., 1997) and the average uplift rate of the entire chain during Quaternary times can be estimated at 1 mm/yr.

From a geomorphological point of view, the southern Apennines are characterised by an asymmetric topographic profile. The summit line of the mountain belt is markedly shifted toward the inner (i.e. Tyrrhenian) margin, and does not correspond to the regional water-divide. Consequently, the outer flank of the chain has a greater length and a lower mean gradient than the opposite one (Amato et al., 1995). The highest summits are about 2000 m a.s.l., whereas the mean elevation of the whole belt is about 650 m a.s.l. (Amato and Cinque, 1999).

The mountain belt tops are often characterised by a gentle topography mainly represented by relics of an ancient erosional landsurface, which unconformably cuts lithological contacts, high-angle faults and other tectonic structures (Brancaccio et al., 1991; Russo and Schiattarella, 1992; Amato and Cinque, 1999; Ascione and Romano, 1999, among others). The regional uplift suspended the ancient erosional base level to which this gentle palaeo-landscape was related, triggering a new morphogenetic stage. The erosional landsurfaces are arranged along the entire orogenic belt in several superimposed generations. In fact, they are located at different elevations both around the top of the

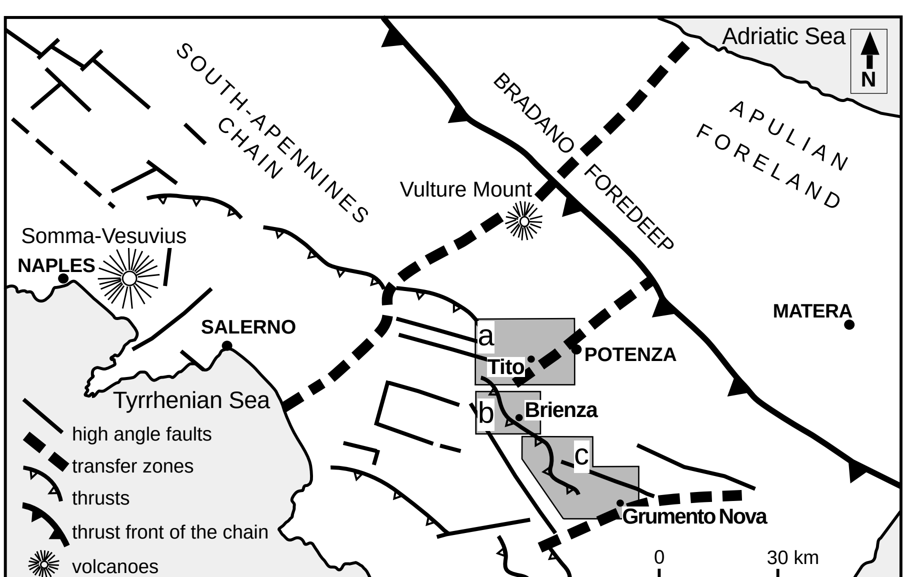

Fig. 1. Tectonic sketch map of the southern Apennines. The study areas are reported in the frames (from north to south): (a) Tito-Picerno Valley and Pignola basin; (b) Pergola–Melandro valley; (c) high Agri valley.

mountains and along the flanks of the valleys. These landsurfaces are formed of many relics isolated by fluvial dissection and faulting, reaching a maximum size of some tens of square kilometres, and are elevated 500–1500 m above the valley floors from the Tyrrhenian flank of the chain to the foredeep (Amato and Cinque, 1999).

In the axial zone of the chain, in which all the study areas are included (Fig. 1), both Mesozoic to Tertiary shallow-water carbonates and coeval pelagic successions crop out. The platform limestone and dolomite mainly constitute the western flanks of the Melandro and Agri valleys, whereas the deep-sea carbonate and siliceous successions (*Lagonegro units*) form the eastern slopes. The Tito–Picerno area and Potenza basin are located inside the outcrop area of the Lagonegro units, unconformably covered by Pliocene marine and Pleistocene continental clastics. In all these areas the erosional landsurfaces are significantly present. The axial zone was affected by strike-slip faulting during late Pliocene–early Pleistocene times, followed by extensional tectonics from middle Pleistocene to Present (Schiattarella, 1998; Giano et al., 2000). The representative Lagonegro-type succession analysed in this work to estimate tectonic loading crops out in the Lucanian Apennine, between Potenza town and Sellata mountain pass (*Pignola–Abriola facies*, after Scandone, 1972).

3. Morphostructural analysis

The arrangement of erosional and depositional landsurfaces at different heights along the axial zone of the Lucanian Apennine has been detected on the bases of both field survey and map analysis. The investigations have been focused along two transects with different orientations (Fig. 2), which cross, respectively, the valleys of Pergola–Melandro and Tito–Picerno streams and the high valley of the Agri River, because of the capability of this kind of intermontane basins to record changes in the erosion base level during the last 2 Ma. Other geological and geomorphological observations have been carried out in the adjoining areas, such as the Potenza piggy-back basin, where the erosional landsurfaces cut prevalently Pliocene clastics, and the Pignola endoreic basins, where the surfaces analysed for rates calculations represent also the depositional top of Quaternary lacustrine deposits. These surfaces have been used as chronological markers to retrace tectonic and morphogenetic events starting from late Pliocene and to calculate regional and local uplift rates of the axial zone of the chain.

The 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 landsurfaces. In some cases, vertical erosion (i.e. incision) rates have been also calculated and converted in local uplift rates assuming that eustatic changes did not produce relevant effects in this sector of the orogen.

The aliquots related to the local uplift often indicate the amount of uplift due to faulting. Therefore, it is possible to separate the uplift due to the regional raising from the effects of local tectonics. Two detailed morphometric profiles have been drawn intercepting NW–SE trending basin-border faults of the Melandro and Agri valleys (Fig. 3). The estimation of the total offsets produced by faulting allowed calculation of the slip rates along the fault planes and the comparison of these data with the local uplift rates. The last kinematics of the analysed faults is expressed by normal slip responsible for major Quaternary dislocations and basin opening during middle to late Pleistocene times (Giano et al., 2000). Former neotectonic deformational stages affected the study areas (Giano et al., 1997) and the whole south-Apennines chain (Schiattarella, 1998) starting from the late Pliocene, but their strike-slip kinematics with horizontal offsets of few kilometres did not favour the relief growth and the creation of large intermontane basins like those generated during middle–late Pleistocene times. This is also documented by low values of fault activity during late Pliocene–early Pleistocene time (Fig. 4).

3.1. Tito–Picerno valley

The valley of the Tito–Picerno stream is a NW–SE trending morphological depression (Fig. 1) mainly cutting Pliocene to Pleistocene clastic successions ascribed to the homonymous sedimentary basin. Four orders of polygenic landsurfaces, relics of which are well preserved along the water divides and suspended on the present valley floor, are recognizable (S1–S4, A–A′ profile in Fig. 2). Three of them are erosional (S1–S3) whereas the lowest (S4) is depositional (Table 1). According to previous regional interpretations (Brancaccio et al., 1991; Santangelo, 1991; Amato and Cinque, 1999), the ages of these landsurfaces are included in a time span ranging from 1.8 to 0.125 Ma.

Uplift rates calculation (Table 1) indicates an increase of the regional raising in a time span from 1.2 to 0.8–0.7 Ma (Fig. 4) and a constant rate of the local uplift. Therefore, the total amount of uplift can be confidently ascribed to the raising of the entire chain.

3.2. Pergola–Melandro valley

The valley of Pergola and Melandro rivers is a NW–SE trending extensional basin (Fig. 1), locally exhibiting 80–150 m thick Pleistocene continental clastic successions (Santangelo, 1991). Similarly to the Tito–Picerno basin, three erosional landsurfaces were also

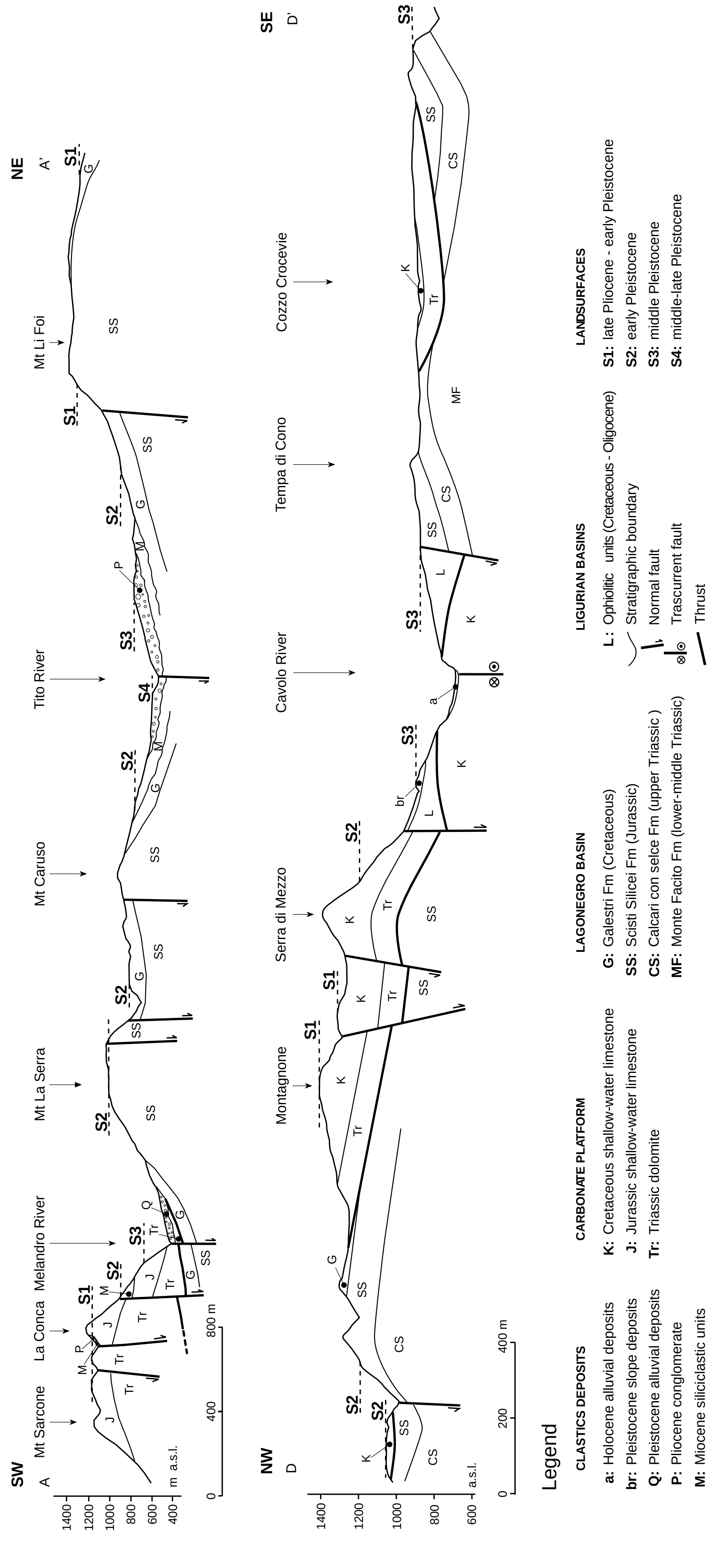

Fig. 2. Morphostratigraphic sections (vertical exaggeration = 2x) from the axial zone of the Lucanian Apennine (see Fig. 7 for location).

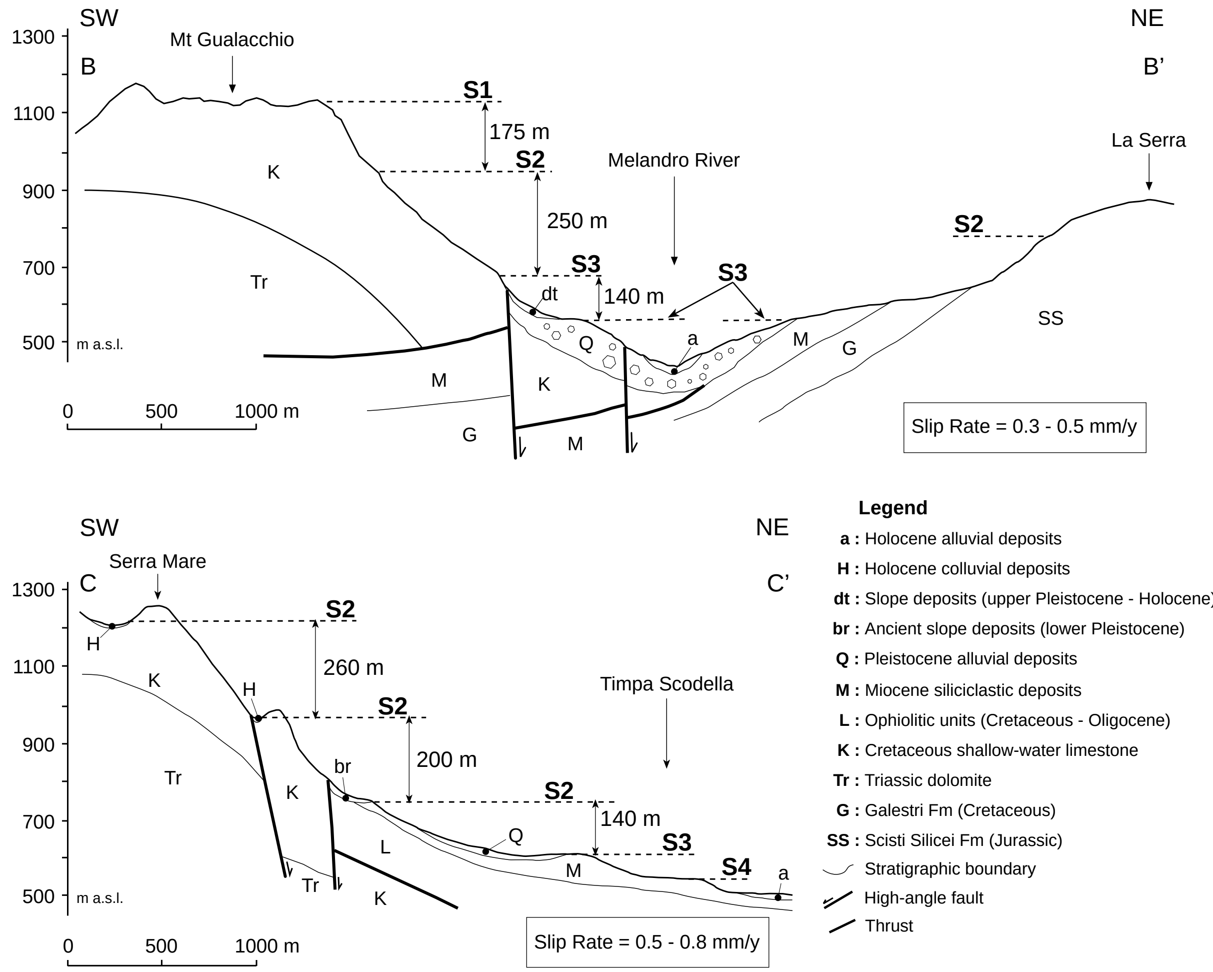

Fig. 3. Detailed morphostratigraphic cross-section (vertical exaggeration = $2x$) from Melandro (B–B′) and Agri (C–C′) valleys, adopted for slip rate calculation (see Fig. 7 for location). Note that the slip rates refer to different time spans (from 1.8 to 1.2 Ma and from 1.2 to 0.8–0.7 Ma for B–B′ and C–C′ profiles, respectively).

identified in the Pergola–Melandro basin (S1–S3, A–A′ profile in Fig. 2). From a morpho-chronological point of view, these gently dipping surfaces can be confidently correlated to those from the basin previously described. The formation of the S1 landsurface can be ascribed to the late Pliocene–early Pleistocene, as inferred by the presence of lower–middle Pliocene clastic deposits in La Conca site (Fig. 2) which were involved in the planation of the 1200 m a.s.l. palaeosurface (S1). Adopting a counting-from-the-top criterion and regional-scale basin correlations, the S2 and S3 landsurfaces ages can be estimated respectively at 1.2 and 0.8–0.7 Ma.

The strong analogies between the Pergola–Melandro and Tito–Picerno basins suggest a similar morphotectonic evolution. The B–B′ morphometric profile crosses the basin-border fault system responsible for the creation of the accommodation space for the Quaternary sediments (Fig. 3). Data about fault system activity show an increment from 0.3 to 0.5 mm/yr in the time span of 1.8–1.2 Ma (Fig. 4) and suggest that this system realised a small offset, compatible with strike-slip faulting acting in the axial zone of the chain during early Pleistocene (Schiattarella, 1998).

3.3. *The high Agri valley*

The high valley of the Agri River (Fig. 1) is a NW–SE trending intermontane basin filled up with middle–upper Pleistocene continental clastic deposits (Di Niro et al., 1992). Tectonics has strongly controlled geomorphological and sedimentary evolution of the basin up to the present (Di Niro and Giano, 1995; Giano et al., 1997, 2000; Cello et al., 2000). The genesis and the early Pleistocene evolution of the Agri basin were controlled by left-lateral strike-slip N120°-trending master faults, reactivated as normal faults since middle Pleistocene times, as observed on a regional scale (Schiattarella, 1998).

Three erosional landsurfaces (S1–S3) can be identified in the D–D′ morphometric profile (Fig. 2) across the

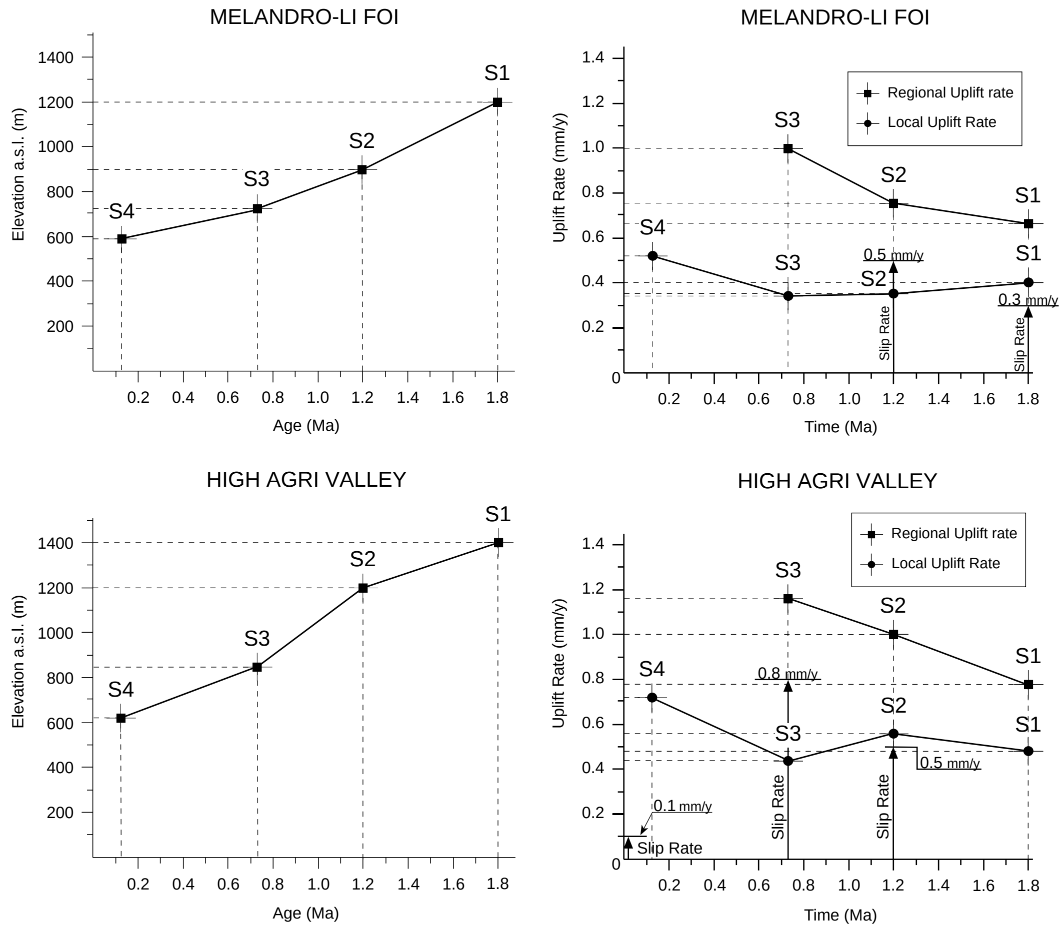

Fig. 4. Diagrams showing the relationships between elevation and age of the landsurfaces from the study areas and the variation of the related regional and local uplift rates during Quaternary.

Table 1
Landsurfaces-related morphometric parameters, ages and uplift rates

Erosional and depositional landsurfaces	Elevation range (m)	Mean elevation a.s.l. (m)	Age (Ma)	Local uplift rate (mm/yr)	Regional uplift rate (mm/yr)
Tito–Picerno basin and Pergola–Melandro valley					
S1	1250–1150	1200	1.8	0.40	0.66
S2	1025–750	900	1.2	0.35	0.75
S3	750–710	720	0.73	0.34	0.99
S4	575–610	590	0.125	0.52	
High Agri valley					
S1	> 1300	1400	1.8	0.48	0.78
S2	1250–1000	1200	1.2	0.56	1.0
S3	950–750	850	0.73	0.44	1.16
S4	650–580	620	0.125	0.72	

southwestern side of the valley (Maddalena Mts). These landsurfaces are coeval with those surveyed in the basins previously described (Table 1), as evidenced by their elevation and morphological characteristics. An additional both depositional and erosional landsurface (S4), forming the depositional top of middle Pleistocene conglomerates and cutting Miocene siliciclastic deposits, is localised at 580–650 m a.s.l., and can be dated at 0.125 Ma.

Regional and local uplift rates calculated for these landsurfaces range from 0.44 to 1.16 mm/yr (Table 1), thus showing the highest values in the investigated area. The regional uplift rate shows a constant increase whereas the local uplift rate is fluctuating (Fig. 4). Slip rates calculated on the SW valley flank fault system vary from 0.5 to 0.8 mm/yr in the time span from 1.2 to 0.8–0.7 Ma (Fig. 3), reaching or exceeding the values of the local uplift rates and therefore accounting for the major part of the total uplift gained during middle Pleistocene times. It is worthy to note that in the last 30,000 yr the same fault system was characterised by a slip rate strongly decreased up to 0.1 mm/yr (data from Giano et al., 2000).

4. Tectonic loading

When sedimentary basins fill and subside, clay minerals undergo diagenetic and very low-grade metamorphic reactions. Such reactions are equivalent to those of organic materials that also undergo a series of irreversible reactions in response to burial and/or tectonic loading. Reactions in both clay minerals and organic material are irreversible under normal diagenetic and anchizonal conditions, so that uplifted sequences generally retain indices and fabrics indicative of maximum maturity and burial. Systematic correlation between mineral and organic maturity indicators represents a useful tool for integrating the basin maturity studies of the mineralogists and the petroleum geologists. Since clay minerals are almost invariably present in basinal sediments, the most common approach is the mineralogical one. Rough estimation of temperatures and determination of diagenetic–metamorphic degree in clay-rich sediments using clay minerals is a well-known and widely used approach for determining the exhumation history of mountain chains. However, data from many sources (Essene and Peacor, 1995; Frey and Robinson, 1999; Di Leo, 2001, for a review) suggest that phyllosilicates in diagenetic and very low-grade metamorphic conditions do not reflect thermodynamic equilibria and consequently the percentage of illitic layers in illite/smectite (I/S) mixed layers, illite and chlorite "crystallinity", clay polytypism are mainly qualitative indicators of the stages the investigated phyllosilicates have reached through a series of metastable mineral reactions (Merriman and Peacor, 1999). Despite this, the illite "crystallinity" and percentage of illitic layers in I/S mixed layers as well as white mica polytypism are useful indicators of burial depth in different geotectonic environments.

4.1. Materials and methods

Fifty-eight clay-rich and shale samples were collected from the entire Pignola–Abriola succession. Three samples came from the *Monte Facito* Formation, 18 samples came from the *Calcari con selce* Formation, 31 samples came from the *Scisti silicei* Formation, and six samples came from the *Galestri* Formation.

The mineralogy of the bulk samples and of the <2 μm grain-size fraction was obtained by XRD analysis (Siemens D5000, CuK_α radiation, graphite secondary monochromator, sample spinner) and the semi-quantitative distribution of the mineralogical components (Fig. 5), has been evaluated following Laviano (1986). Petrographic and textural observations showed that all the samples have not suffered severe deformation and are free of veins.

In order to determine the degree of post-sedimentary processes affecting the samples analysed in the present study and the range of temperature they experienced, the most widely XRD-based illite "crystallinity" technique (Merriman and Peacor, 1999, and references therein) were used. The illite "crystallinity" technique measures changes in the shape of the first basal reflection (approximately 10 Å) of dioctahedral illite–muscovite. The most widely adopted method for measuring the 10-Å peak profile is still the one first used by Kübler (1967), which measured the width of the 10-Å peak at half-height above the background (FWHM). Although this method proved to be an easy-to-use measure of grade of diagenesis and incipient metamorphism of clastic rocks, it is not a direct measure of the "crystallinity". This is why, hereafter, the term illite "crystallinity" will be substituted by the term Kübler Index (KI), where KI values are expressed in $\Delta°2\theta$.

KI values in the clay-rich levels from the Pignola–Abriola succession were measured on the <2 μm size fraction XRD patterns from oriented mounts. The same patterns were also used to estimate the percentage of illite in the mixed layers I/S, as another indicator of diagenesis and low-grade metamorphism (cf. Velde, 1992; Pollastro, 1993; Essene and Peacor, 1995), which allows measurement of the smectite-to-illite-reaction progress. The oriented mounts were prepared as follows. The material was crushed in a hand mortar and then transferred to a plastic container for ultrasonic treatment for 2–3 min. After settling, the suspension containing the <2 μm grain-size fraction was decanted, pipetted and dried at room temperature on glass slides to produce a thin layer, highly oriented aggregate with a particle density of at least 3 mg/cm^2. The KI was measured on both air-dried and ethylene-glycol solvated slides following analytical technique and grain-size fractions recommendations as specified by Kisch (1991). A good agreement was observed between air-dried and ethylene-glycol measurements of illite crystallinity ($R^2 = 0.907$).

The results were calibrated using interlaboratory standards (Warr and Rice, 1994). The approached proposed by Warr and Rice (1994) attempted to remedy some of the problems relative to KI measurements with a set of four interlaboratory standards (Crystallinity Index Standard, CIS) representing metapelites from late diagenetic zone to the epizone, plus a muscovite flake.

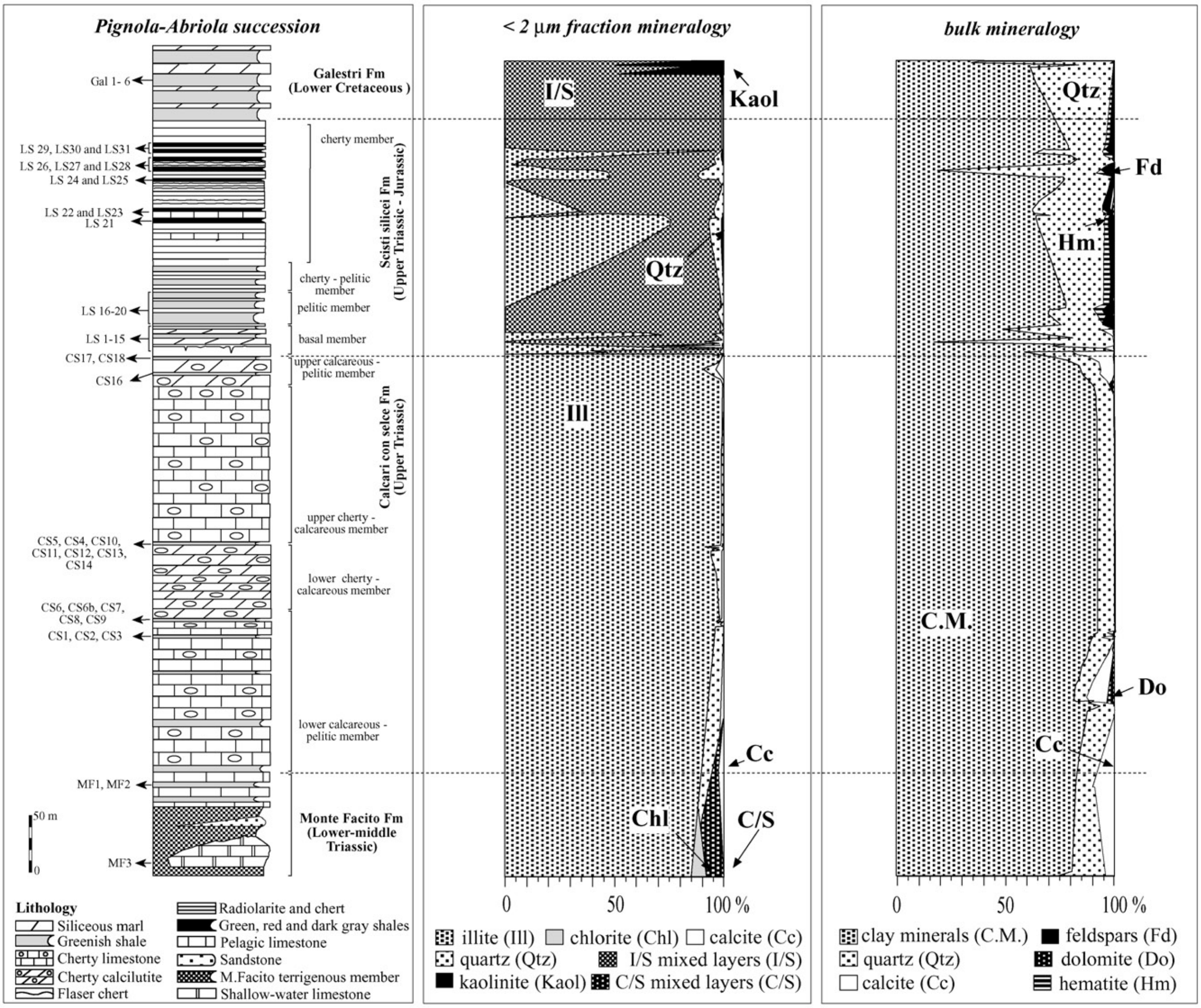

Fig. 5. Variation of the bulk and less than 2-μm mineralogy of pelitic layers in the Pignola–Abriola section.

These were prepared following the same procedure adopted for the samples and analysed using the same machine conditions used to collect the XRD patterns of samples. By comparing the observed KI values with those reported by Warr and Rice (1994) for the five standards a regression was derived, which allowed calibration of KI values (Di Leo, 2001).

The percentage of $2M_1$ polytype of white mica was measured using a Nonius PDS X-ray diffractometer. XRD patterns of randomly oriented $<2\mu m$ fraction side-packed mounts were analysed following the quantification methods used at the Mineralogy Department of the Natural History Museum in London (Cressey and Schofield, 1996; Batchelder and Cressey, 1998) and the LINKFIT program.

4.2. Estimate of tectonic loading

The mineralogy of clay-rich beds from Lagonegro units is mainly composed of illite and quartz (Fig. 5). Calcite is observed in the lower part of the Pignola–Abriola succession, i.e. in the *Monte Facito* and *Calcari con selce* formations, and plagioclases are only observed in the pelitic and cherty members from *Scisti silicei* Formation (for member definition see Di Leo et al., 2002) and in the *Galestri* Formation. Clay minerals are not homogeneously distributed along the succession (Fig. 5). In the *Monte Facito* and *Calcari con selce* Formations illite prevails, in the *Scisti silicei* Formation I/S mixed layers are dominant, and in the *Galestri* Formation kaolinite as well as I/S mixed layers are abundant.

Illite "crystallinity" (expressed as KI values), % of illitic layers in I/S mixed layers, and percentage of $2M_1$ polytype were measured in the above-mentioned formations as indicators of diagenesis and low-grade metamorphism and to estimate tectonic loading experienced by the Mesozoic pelagic successions (Lagonegro units). Starting from the stratigraphically lower *Monte Facito* Formation to the upper *Galestri* Formation (Fig. 6), KI values show a clear increasing trend with values ranging between 0.6 and 1.1 $\Delta°2\theta$ (mode = 0.88 $\Delta°2\theta$). Small amounts of coarse-grained illite (Gharrabi and Velde, 1995) with KI values $<0.4\ \Delta°2\theta$ were also found in some samples from the upper part of the Pignola–Abriola succession, i.e. in the cherty-member of *Scisti silicei* and in the *Galestri* formations (Fig. 6). The stratigraphic position of the samples where the coarse-grained illite was observed—samples containing illite with KI values typical of anchizone were found in a stratigraphically higher position with respect to those containing illite with KI typical of diagenetic zone—suggests this mineralogical phase is mainly detrital. This illite was not taken into account in defining maximum temperatures and tectonic loading. The KI values observed all along the Pignola–Abriola succession suggest temperatures in the range of 100–180°C. Relationships between temperatures and KI values have been defined by many authors in different geotectonic settings (e.g. Jaboyedoff and Thélin, 1996; see also Frey and Robinson, 1999, for a review). However, the basin maturity chart showing correlation of reaction progress in the smectite–I/S–illite series with temperature and maturation stages and some organic maturity indices proposed by Merriman and Frey (1999) seems to be, so far, the most exhaustive, since it was defined on data sets from a wide number of geological settings where clay minerals have been used to define temperature and infer tectonic loading.

The percentage of illitic layers in I/S mixed layers, estimated following Moore and Reynolds (1997) suggestions, is in the range of 75–90% ($R = 1$ and 3 ordering, Reickeweite number) for the *Scisti silicei* Formation and decreases to 60–70% ($R = 0.5$–1 ordering) upsection, i.e. in the samples from the *Galestri* Formation (Fig. 6). The

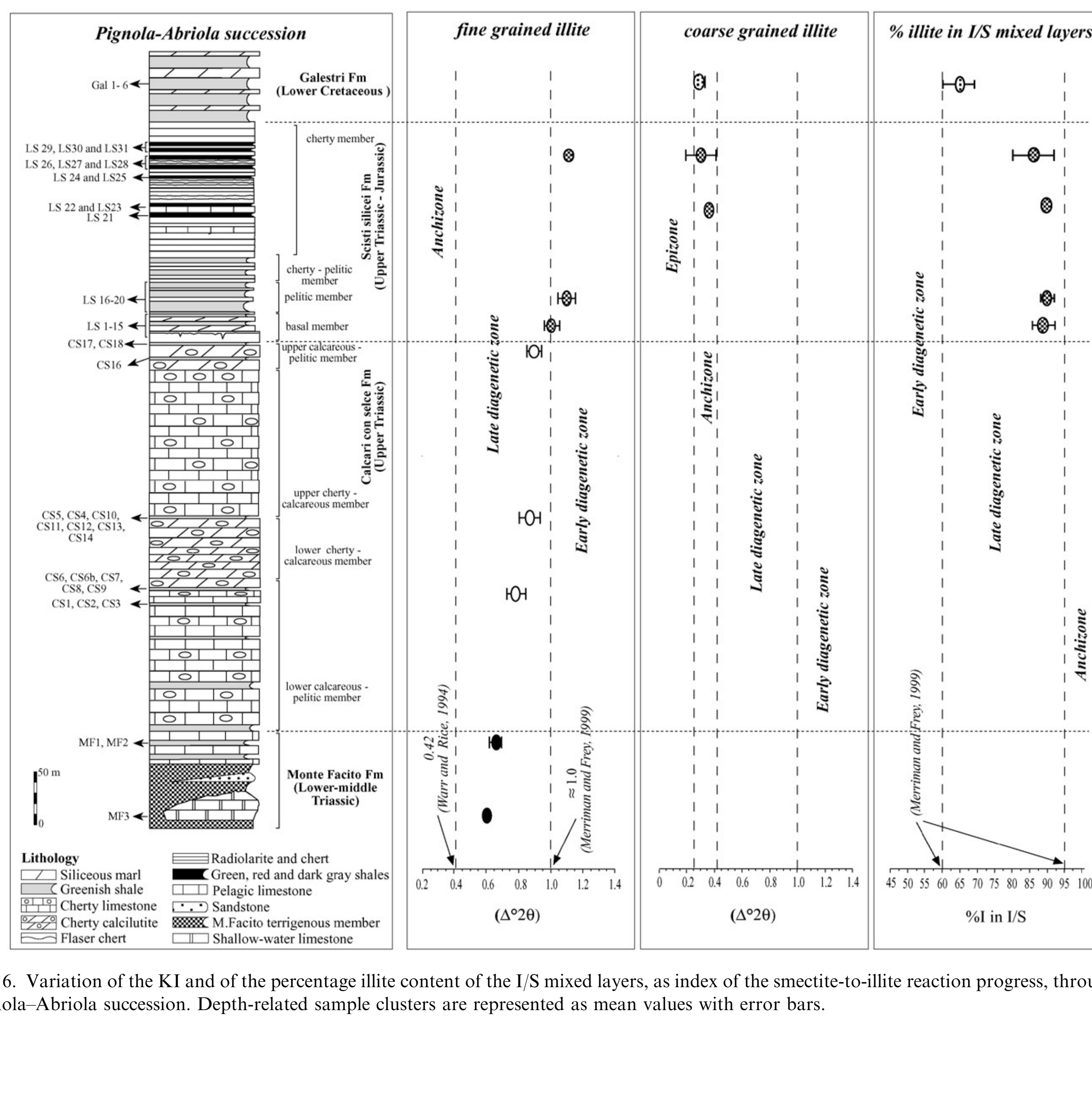

Fig. 6. Variation of the KI and of the percentage illite content of the I/S mixed layers, as index of the smectite-to-illite reaction progress, through the Pignola–Abriola succession. Depth-related sample clusters are represented as mean values with error bars.

reaction in which smectite is a reactant and illite a product, recognised to occur over a predictable range of depth in mudstones, is here used as another comparative "geothermometer" jointly with the Kübler (1967) Index.

Usually, the smectite-to-illite reaction concerns the diagenetic range, whereas the KI improvement and the mica polytype $2M_1$ percentage variation mainly applies to the early stages of metamorphism, i.e. very low (anchizone) and low (epizone) grades (Chamley, 1995). Many papers have attempted to relate temperature to % of illitic layers in I/S mixed layers. The classic paper by Hower et al. (1976) emphasised that the depth-related transformation occurred over the temperature range of approximately 60–90°C. Weaver and Broekstra (1984) proposed to divide the clay diagenetic evolution into three stages based on the I/S ratio in the $<2\ \mu m$ size fraction: (i) "early diagenesis", where a regular mixed-layer I/S is, or should be, present (approximately 60% illite layers; 90–140°C); (ii) "middle diagenesis", which ranges from the first development of a regular mixed-layer phase to the disappearance of a discrete glycolated peak for the mixed-layer phase (illite layers > 90%; max temperature 200°C); (iii) "late diagenesis", where the glycolated mixed-layer phase appears as an integral part of the illite peak ($<10\%$ smectite layers $\sim$250–280°C). On the other hand, Jaboyedoff and Thélin (1996) proposed relationships between the evolution of I/S mixed-layer phase, KI and mica polytypes and temperature and burial depth/tectonic loading, defined in a collisional setting, where the range of temperatures for the diagenetic zone 100/130°C–200/250°C correspond to a range 60/80–96/98% of illitic layers in I/S mixed layers and to a range 1–0.39 $\Delta°2\theta$ of KI. Further, Merriman and Frey (1999), based on data from a wider number of geological settings, referred a maximum temperature of 180°C to % of I in I/S mixed layers in the range 60–90%. Similarly to the KI, to estimate temperatures from clay minerals evolution in the Pignola–Abriola succession, the relationships between temperature and % of I in I/S mixed layers proposed by Merriman and Frey (1999) were adopted, since they refer to a large variety of geological settings and are therefore more representative of the evolution of such minerals through time. By integrating data relative to the percentage of illitic layers in I/S mixed layers with KI values, the temperatures experienced by the Lagonegro units can be estimated in the range 100–180°C.

Another indicator of diagenesis and low-grade metamorphism, commonly used in studies dealing with reconstruction of geological processes, is based on the definition of the white mica polytypes, although polytypic sequence should not be used other than as indicator of reaction progress since accurate correlation with temperature is not possible (Merriman and Peacor, 1999). The existence of an apparent prograde sequence of polytypism for white micas from $1M_d$ to 1M to $2M_1$ has been well demonstrated (cf. Velde and Hower, 1963; Hoffman and Hower, 1979). The abundances of white mica polytype $2M_1$ (in the range of 10–35%) estimated in the *Monte Facito*, *Calcari con selce* and *Scisti silicei* Formations are consistent with temperatures in the range 100–180°C. Starting from the temperature estimates by clay minerals-based geothermometers and considering an average geothermal gradient of 20–30°C/km (Mongelli et al., 1996), a diagenetic/tectonic evolution corresponding to about 4–5 km tectonic loading can be hypothesised for the Pignola–Abriola succession.

5. Discussion and conclusions

The values of the Quaternary uplift rates of the south-Apennines axial zone (Fig. 7) vary from a minimum of 0.2 mm/yr (Pignola basin) to a maximum of about 1.2 mm/yr (Agri valley). Intermediate values (0.5–0.7 mm/yr relative to Mt Li Foi area, Tito–Picerno and Melandro valleys) have been calculated for the other studied areas. An increasing trend of uplift rate values toward south can be also observed (Fig. 7).

In the Melandro basin and adjacent Maddalena Mts, the same rates ($\sim$0.6 mm/yr) have been obtained for a large time span (about 2 Ma), using geomorphological features and late Pliocene to Quaternary successions involved in landsurface planation (see also Santangelo, 1991; Amato and Cinque, 1999), in good agreement with data from other sectors of southern Italy (Cucci and Cinti, 1998; Amato, 2000).

The slip-rate value of 0.3 mm/yr from the Pergola–Melandro basin relative to 1.8 Ma landsurfaces is lower than those calculated by means of more recent features. Such a value suggests low activity of faults and small vertical displacements at that time, in agreement with strike-slip faulting acting during early Pleistocene (Schiattarella, 1998). The extensional tectonics responsible for major vertical displacements may be set up at about 0.8–0.7 Ma in the axial zone of the chain. The highest slip-rate value of 0.8 mm/yr is in fact recorded in the Agri River high valley at that time. In the same area, the slip rate slowed down to 0.1 mm/yr in the last 30,000 yr (data from Giano et al., 2000). It is remarkable that in the external sectors of the chain the tectonic regime changed from transcurrent to extensional during the time span between 0.7 and 0.5 Ma (Pieri et al., 1997), as a consequence of a diachronous activation of normal faulting from inner to outer areas.

On this basis, it can be affirmed that in the Melandro valley a comparable partitioning between local (i.e. tectonic) and regional uplift has to be invoked to justify the present elevation of the relict morphological features whereas the major part of the relief energy in the Agri River high valley can be ascribed to the activity

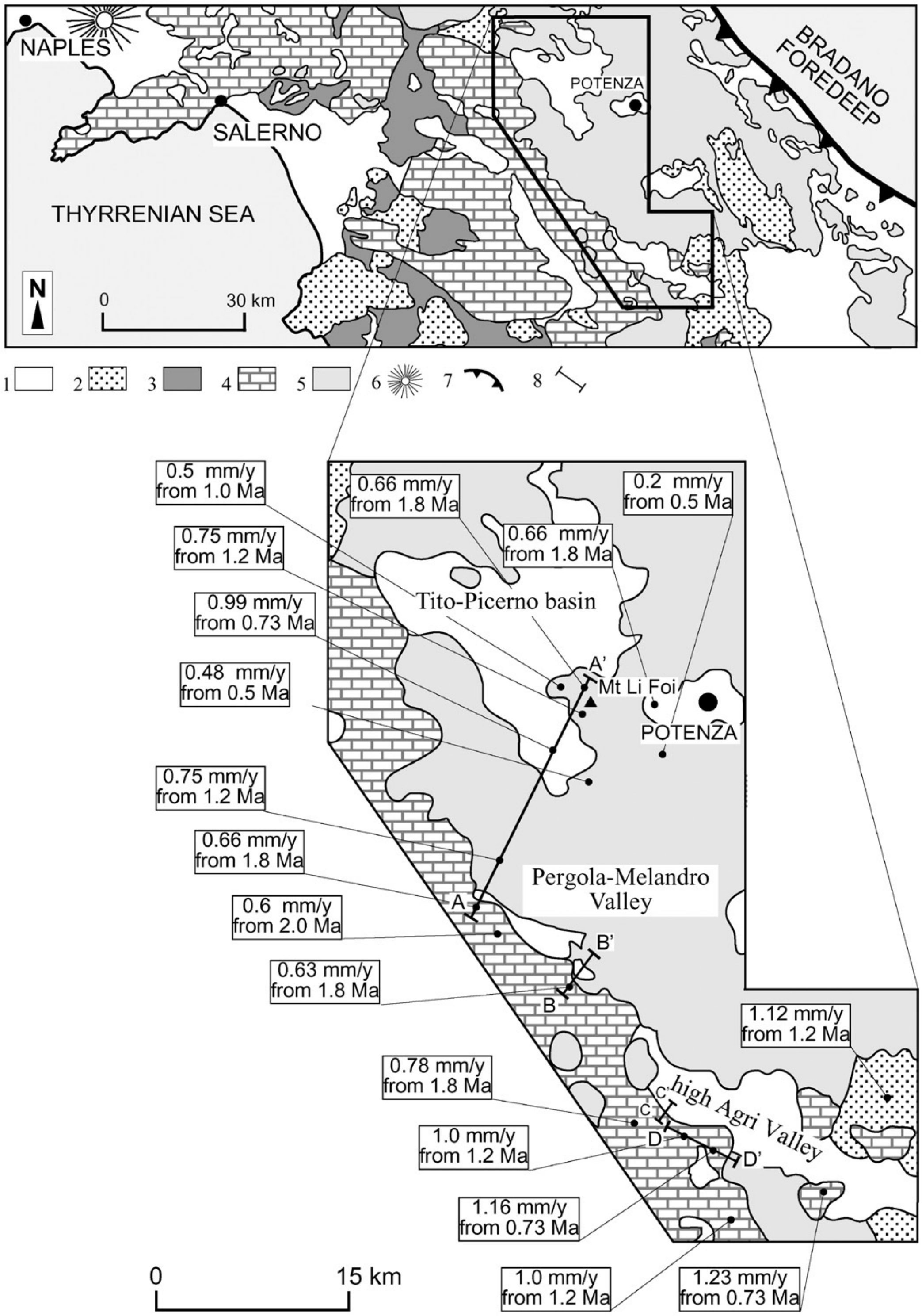

Fig. 7. Arrangement of the uplift rate values along the axial zone of the Lucanian Apennine. Legend of the sketch maps: 1. Plio-Quaternary clastics and Quaternary volcanics; 2. Miocene syntectonic deposits; 3. Cretaceous to Oligocene ophiolite-bearing internal units (Ligurian units); 4. Meso-Cenozoic shallow-water carbonates of the Campania–Lucania platform; 5. Lower-middle Triassic to Miocene shallow-water and deep-sea successions of the Lagonegro, Numidian, and Irpinian basins; 6. Volcano; 7. Thrust front of the chain; 8. Traces of the morphometric profiles shown in Figs. 2 and 3.

of basin-border faults. Yet, also in this area the local morphostructural offsets have to be coupled with regional uplift of the orogen to reach the total amount of Quaternary uplift. The southward increasing uplift rate trend may be related to the higher faulting activity in the southernmost part of the investigated area. In any case, during the last 2 Ma, the total uplift of the axial zone of the Lucanian Apennine is of about 1.2–1.3 km, with local peaks of 1.5 km.

On the other hand, in the pelitic beds from Lagonegro units the mineral assemblage of the $<2\mu m$ fraction, mainly composed of illite and I/S mixed layers, the percentage of illitic layers in I/S mixed layers (60–90%, R ordering in the range of 0.5–3), the illite crystallinity (KI mode $= 0.88\ \Delta°2\theta$) as well as the percentage of white mica polytype $2M_1$ (in the range of 10–35%), are consistent with a diagenetic/tectonic evolution corresponding to 4–5 km burial depth.

The Quaternary uplift and the related erosion rates of the southern Apennines are unquestionably due to extensional tectonics coupled with thermal/isostatic regional raising and, in a minor extent, due to strike-slip faulting acting in the earlier deformational stage of the south-Apennines chain. The gap of several km deriving from the comparison between uplift rates and tectonic loading values may be explained only with different exhumation modalities starting from late Miocene times. This age can be obtained assuming a fixed rate of 0.6 mm/yr, which represents the best long-term estimate for the axial zone of the chain. Going back in time using such a conservative rate to get a denudation value of about 4–5 km, Tortonian age is reached. At that time, contractional tectonics was still active in this sector of the southern Apennines. Tectonic erosion (Mancktelow, 2000, and references therein) may be taken into account for a reliable explanation of the discrepancy between the different data sources.

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