GEOLOGICA CARPATHICA, FEBRUARY 2011, 62, 1, 17–26 doi: 10.2478/v10096-011-0002-2

New morphostratigraphic and chronological constraints for the Quaternary paleosurfaces of the Molise Apennine (southern Italy)

PIETRO P.C. AUCELLI[1], VINCENZO AMATO[2], MASSIMO CESARANO[2], GERARDO PAPPONE[1], CARMEN M. ROSSKOPF[2], ELDA RUSSO ERMOLLI [3,4] and FABIO SCARCIGLIA[5]

[1]Dipartimento DiSAm, Università degli Studi di Napoli Parthenope, Centro Direzionale, 80100 Napoli, Italy; pietro.aucelli@uniparthenope.it; gerardo.pappone@uniparthenope.it
[2]Dipartimento S.T.A.T., Università degli Studi del Molise, Contrada Fonte Lappone, 86090 Pesche (IS), Italy; vincenzo.amato@unimol.it; cesarano@unimol.it; rosskopf@unimol.it
[3]Dipartimento di Arboricoltura, Botanica e Patologia vegetale, Università di Napoli, Federico II, via Università 100, 80055 Portici, Italy; ermolli@unina.it
[4]Département de Préhistoire du Muséum National d'Histoire Naturelle, USM103—MNHN, UMR7194, CNRS, Institut de Paléontologie Humaine, rue René Panhard 1, 75013 Paris, France
[5]Dipartimento di Scienze della Terra, Università della Calabria, Via P. Bucci, Cubo 15B, 87036 Arcavacata di Rende (CS), Italy; scarciglia@unical.it

(Manuscript received May 27, 2010; accepted in revised form November 5, 2010)

Abstract: The Molise Apennines feature numerous relicts of paleosurfaces, mostly of erosional origin, which represent the remnants of gently-rolling ancient landscapes now hanging at different altitudes above the local base-levels of erosion. Their genesis can be related to prolonged periods of relative tectonic stability alternating with periods of uplift, or to the interplay between steady tectonic uplift and climatic fluctuations. Four orders of paleosurfaces were recognized: I (>1,100 m a.s.l.), II (900–1,000 m a.s.l.), III (750–850 m a.s.l.), IV (600–720 m a.s.l.). The most ancient orders (I and II) are cut into the bedrock and are located at the top of the Matese and Montagnola di Frosolone massifs. The youngest paleosurfaces (III–IV), partially cut into Quaternary deposits, are found along the valley flanks of the main river systems and within the Boiano, Carpino, Isernia and Sessano intramontane basins. The present study deals with the dating of the Sessano Basin Paleosurface (SBP) which is related to the IV order and is cut into the basin infill. The $^{40}Ar/^{39}Ar$ age of a tephra layer (437±1.9 ka), intercalated at the top of the succession, supported by archaeo-stratigraphic, palynological and paleopedological data, allowed the SBP surface to be constrained to 350–300 ka. The SBP chronological position represents an important morphostratigraphic marker: it is the first *ante quem* and *post quem* date that allows the chronological position of the other orders of paleosurfaces to be better constrained.

Key words: Quaternary, Italy, Molise Apennine, paleosurfaces, paleopedology, morphostratigraphy.

Introduction

In recent decades, the interest of geomorphologists in long-term and regional landscape reconstructions has opened up new perspectives for the study of the relationship between tectonics and exogenous dynamics over geological times (Summerfield 1991; Cinque et al. 1993; Westaway 1993; Ollier & Pain 1996; Amato & Cinque 1999; Bartolini 1999; England & Molnar 1999; Amato 2000; Burbank & Anderson 2001; Schiattarella et al. 2003; Robustelli et al. 2009). The geomorphic markers traditionally used for this purpose are marine terraces and paleosurfaces. According to Widdowson (1997), the term paleosurface indicates "a topographic surface of depositional or erosional origin, recognizable as a part of the geological record, or otherwise of demonstrable antiquity and of regional significance, which displays the effects of surface alteration resulting from a prolonged period of weathering, erosion or non-deposition". Although hard to date with respect to marine terraces, paleosurfaces are frequently used in tectonic studies due to their large surface area, which allows geomorphic correlations over long distances and facilitates the recognition of differential tectonic movements. Successful application of stratigraphic techniques may be achieved when it is possible to date the deposits immediately underlying or covering the paleosurface. Provided that they have a well-documented age, paleosurfaces may play a fundamental role in reconstructing the temporal sequences of geomorphological and tectonic events.

In the central and southern Apennines, several morphostratigraphic studies have managed to obtain age estimates for many paleosurfaces, cut both in the chain and foredeep domains (e.g. Brancaccio et al. 1988; Bosi et al. 1996; Amato & Cinque 1999; Basili et al. 1999; Coltorti & Pieruccini 2000; Bartolini et al. 2003, D'Alessandro et al. 2003; Boenzi et al. 2004; Gioia & Schiattarella 2006; Schiattarella et al. 2006). These paleosurfaces represent the remnants of gently-rolling ancient landscapes, generated by fluvio-denudational processes, which are preserved at different altitudes above the local base levels of erosion. In general, their genesis took place during more or less prolonged periods of relative tec-

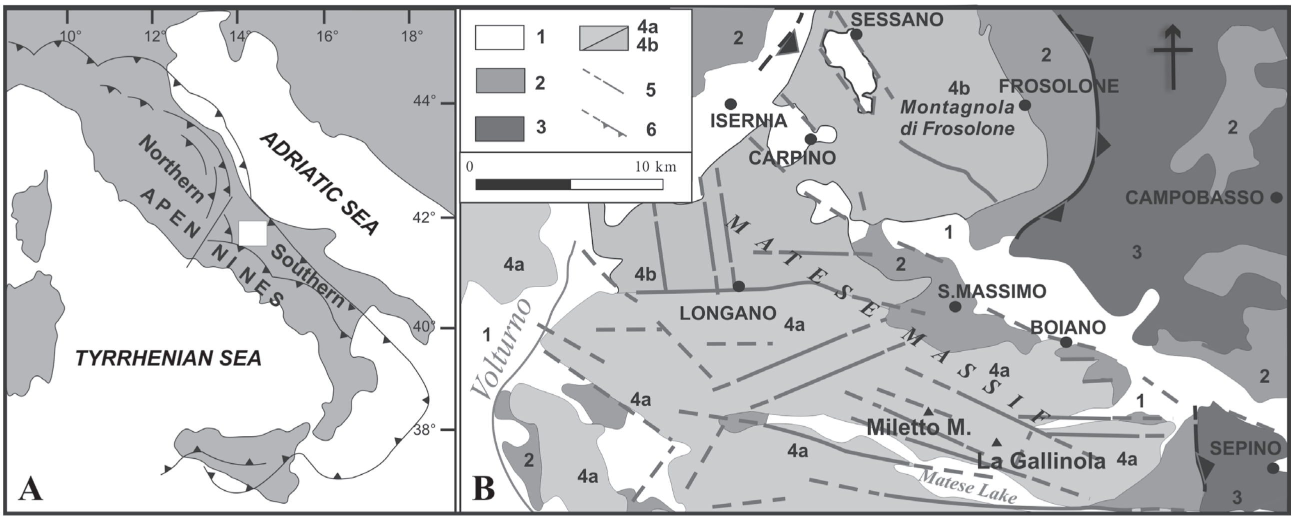

Fig. 1. A — Structural map of Italy and location of the study area; **B** — Geological scheme of the Matese-Frosolone area. Legend: **1** — Alluvial and volcaniclastic deposits (Quaternary); **2** — Foredeep and piggy-back siliciclastic deposits (Miocene); **3** — Clays, marls and limestones of the Sannio Unit (Upper Cretaceous-Miocene); **4** — Limestones, dolomites and marls of the inner carbonate platform (**a**) and carbonate slope deposits (**b**) (Triassic–Miocene); **5** — Main thrusts, dashed where inferred; **6** — Main extensional faults, dashed where inferred.

tonic stability that alternated, during Neogene times, with periods of uplift (Cinque et al. 1993). The most ancient paleosurfaces, often in summit positions (e.g. *Paleosuperficie Auct*.; Cinque et al. 1993; Bosi 2002), are polygenic forms which unconformably cut the deformed units of the Apennine orogene and are found at high altitudes, generally above 1,000 m a.s.l. Other paleosurfaces are much younger and are located along valley flanks or in tectonic depressions at various altitudes above the present local base levels of erosion.

The sector of the Apennine chain located in the Molise region (hereinafter Molise Apennine, Fig. 1) is also characterized by numerous relicts of paleosurfaces both within the mountain belt and along its margins, as well as within the intramontane basins. The areas that preserve various orders of paleosurfaces are typically characterized by a distinct step-like landscape. Even if this pattern clearly testifies to a complex tectonic evolution, it is currently constrained by few — and uncertain — chronological data (i.a. Brancaccio et al. 1979; Brancaccio et al. 2000; Coltorti et al. 2005; Di Bucci et al. 2005). In particular, recent studies by Amato et al. (2010) and Russo Ermolli et al. (2010) have added some new chronological constraints for the Middle Pleistocene paleosurface of the Sessano intramontane basin located along the northwestern margin of the Montagnola di Frosolone massif (Fig. 1).

In this paper, we summarize the results of a geomorphological study in the Molise Apennine focusing on the major relicts of paleosurfaces with a regional significance in order to attribute a relative age to them and thus to reconstruct the main steps of the landscape evolution in the area. In this regard, a fundamental contribution was provided by the multidisciplinary approach used to date one such paleosurface, the Sessano Basin (hereinafter SBP). Our study combined stratigraphic and geomorphic methods, and was supported by pollen and paleopedological analyses, tephrostratigraphy, $^{40}Ar/^{39}Ar$ dating and geoarchaeological contributions.

Geological setting

The Molise Apennine (Fig. 1A) rise in the junction zone between the southern and the central-northern arcs that form the Apennine chain (Patacca et al. 1992). In this zone, the pre-Quaternary bedrock comprises a Meso-Cenozoic carbonate platform and slope-to-basin deposits, cropping out on the Matese and on the Montagnola di Frosolone massifs, as well as Meso-Cenozoic basin deposits of the Sannio Unit and by Miocene foredeep and piggy-back basin deposits (Fig. 1B). The structural setting of the area is the result of a complex deformation due to compressive tectonics from the Miocene to Pliocene (Corrado et al. 1997a; Scrocca & Tozzi 1999; Antonucci et al. 2002). Subsequently, transtensional and extensional tectonics acted, from the Early Pleistocene, mainly along NW-SE and NE-SW oriented alignments, respectively. During extensional tectonics, from the Middle Pleistocene onwards (Corrado et al. 2000; Di Bucci et al. 2002; Amato et al. 2010), several intramontane basins of variable size (Carpino-Le Piane, Isernia, S. Massimo, Boiano and Sessano) developed within the Molise Apennine chain and were gradually filled up by huge Quaternary successions composed of fluvial to lacustrine and volcaniclastic deposits (Brancaccio et al. 1979; Corrado et al. 1997a; Corrado et al. 2000; Di Bucci et al. 2002; Coltorti et al. 2005; Di Bucci et al. 2005; Russo Ermolli et al. 2010).

The Sessano Basin, in particular, characterized by a huge and partially outcropping fluvio-lacustrine succession, was only affected by extensive tectonics during the Middle Pleistocene which caused the tilting of the infilling and extinction of the paleomarsh. After this tectonic event the top of the Middle Pleistocene succession mainly underwent erosion by fluvio-denudational processes, which led to the formation of a wide erosional surface (the SBP), now hanging about 25 m above the present base level (Amato et al. 2010; Russo Ermolli et al. 2010).

The paleosurfaces of the Molise Apennine

The paleosurfaces were studied through field surveys, aerial photos and topographic maps. As shown by Bosi et al. (1996), the main problem in analysing paleosurfaces is the correlation and ordering of the remnants in altitudinal ranges. The criteria adopted in the present study are the following: 1) the geometric relationship and continuity of the paleosurface remnants; 2) the possible correlation on the basis of altitude, bearing in mind the possible gradients of the original surfaces, their position within the local sedimentary sequences and their relationship with local successions that are well correlated; 3) their relationship with geological formations of known chronostratigraphic position and, finally, 4) similarity criteria based on the state of preservation and origin of the single remnants.

Generally, the distinguished paleosurface remnants are gently sloping surfaces (<5°) covering an area ranging between some hundreds and some thousands of m^2. Most of them have an erosional origin, either on carbonate or terrigenous rocks, while those originated by deposition, genetically related to Quaternary continental deposits, are only present at lower altitudes within the main fluvial valleys and the major tectonic depressions. Even if the pre-existing litho-structural rock features have sometimes influenced the extent and regularity of the surfaces, more frequently a clear unconformity between the bedding and the surfaces confirms their origin by erosion. The paleosurfaces are limited by scarps linked to direct tectonic control or generated by base level variations and consequent downcutting due to uplift and/or climatic influence. Alternating phases of dominant planation and downward erosion then generated a typical "terraced" landscape which characterizes wide areas of the Molise Apennine.

The following four orders of paleosurfaces were identified in the Matese and Montagnola di Frosolone massifs, in the upper portion of the Biferno and Trigno valleys (Fig. 2) and in the sector including the Sessano and Carpino Basins and their surroundings (Fig. 3).

I order (>1,100 m a.s.l.)

The I order of paleosurfaces are widespread within the Matese and Montagnola di Frosolone massifs (Figs. 2, 4a and 4b), where they reach up to 2,000 m and 1,400 m a.s.l., respectively. These paleosurfaces, the most ancient of the Molise Apennine, are generally cut into carbonate rocks. Their origin is related to fluvio-denudational processes which inter-

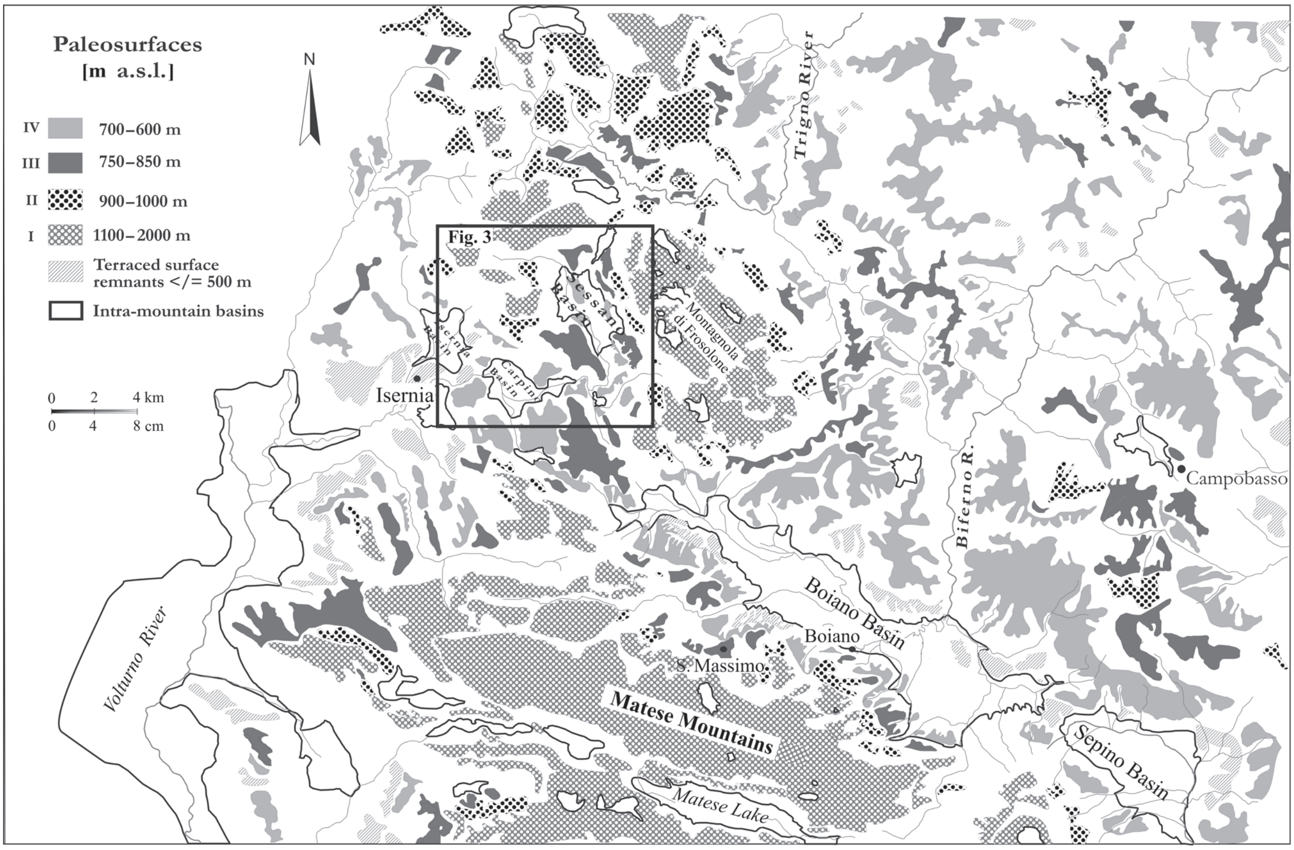

Fig. 2. Distribution of the four orders of recognized paleosurfaces and location of the intramontane and fluvial basins of the Molise Apennine.

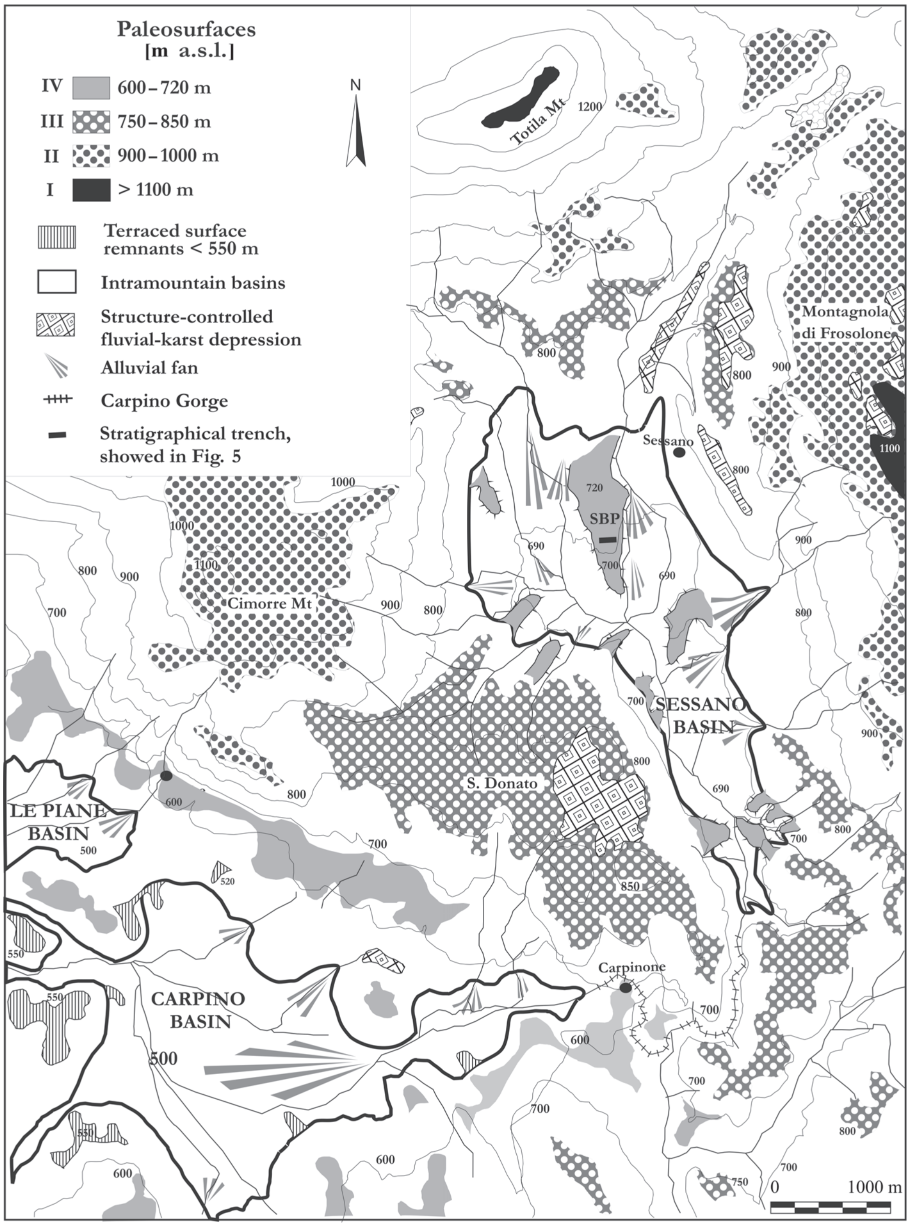

Fig. 3. Detail of the four orders of paleosurfaces in the Sessano-Carpino intramontane basin area.

acted at times with karst and glacial erosion. This interaction results in polygenic landforms often preserving more than one erosional cycle and partially affected by tectonic fragmentation. The difference in altitude among the I order surfaces can be related to differential vertical tectonic movements that affected the Matese and Montagnola di Frosolone massifs during the Apennine formation process. Some geomorphic indicators, such as hanging paleovalleys, provide evidence of the hydrographic network that characterized the chain while the paleosurface was being shaped.

II order (900–1,000 m a.s.l.)

The II order of paleosurfaces are well represented along the carbonate border slopes of the Matese and Montagnola di Frosolone massifs and within the upper mature sectors of the Volturno and Trigno valley systems (Figs. 2, 4a and 4b). Some of them are derived from tectonically lowered I order paleosurfaces, later affected by further modelling and erosion. Within the hilly to low-mountainous sectors, located on the terrigenous deposits of the Sannio and Molise Basin units, strong downfaulting and erosion led to their fragmentation and progressive reduction into small crests and isolated heights. As part of the main water divides, they mainly occur in the upper sector of the Biferno valley system.

III order (750–850 m a.s.l.)

The III order of paleosurfaces are also well represented along the northern slope of the Matese and the border slopes of the Montagnola di Frosolone mountains (Fig. 4a and 4b), as well as along the borders of the Sessano and Carpino Basins (Figs. 3 and 4d). They are also well preserved within the upper portions of the Biferno and Trigno Valleys both in the summit position and along the valley flanks. Generally, these paleosurfaces are cut into the bedrock, apart from the San Massimo paleosurface. The latter, located at ca. 800 m a.s.l. along the northwestern slope of the Matese Mountains and hanging about 300 m above the Boiano Plain, unconformably cut fluvio-palustrine deposits (Fig. 4c). $^{40}Ar/^{39}Ar$ ages after Brancaccio et al. (1979) and Di Bucci et al. (2005) allowed two interbedded volcaniclastic levels to be constrained to 1.0–1.1 Ma and 0.6 Ma.

IV order (600–720 m a.s.l.)

The IV order of paleosurfaces are widespread in the Molise Apennine. Numerous remnants are located along the southern slopes of the Boiano Plain (Fig. 4a) and in the upper sectors of the Biferno and Trigno Valleys where they are often part of the water divide (Fig. 2). Within the Sessano Basin and along its borders (Figs. 3 and 4d), this order is also well represented, at 700–720 m a.s.l., by remnants with a certain areal continuity, cutting both the pre-Quaternary bedrock and the Middle Pleistocene fluvio-palustrine filling. One of

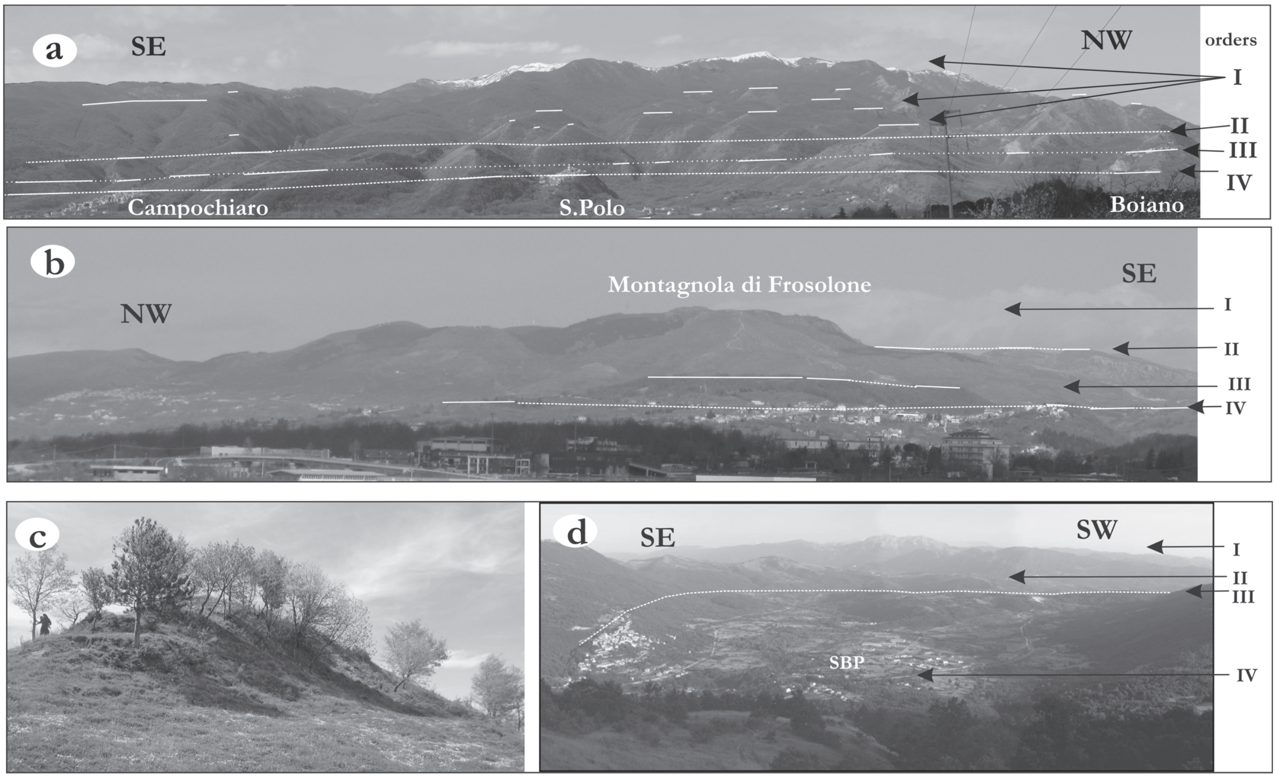

Fig. 4. Views of the paleosurfaces of the Molise Apennine: **a** — remnants along the north-eastern slopes of the Matese Mountains; **b** — remnants along the south-eastern slopes of the Montagnola di Frosolone massif; **c** — top of the fluvio-palustrine succession cropping out near the village of San Massimo at 800 m a.s.l. and referred to the III order of paleosurface; **d** — remnants around and within the Sessano Basin.

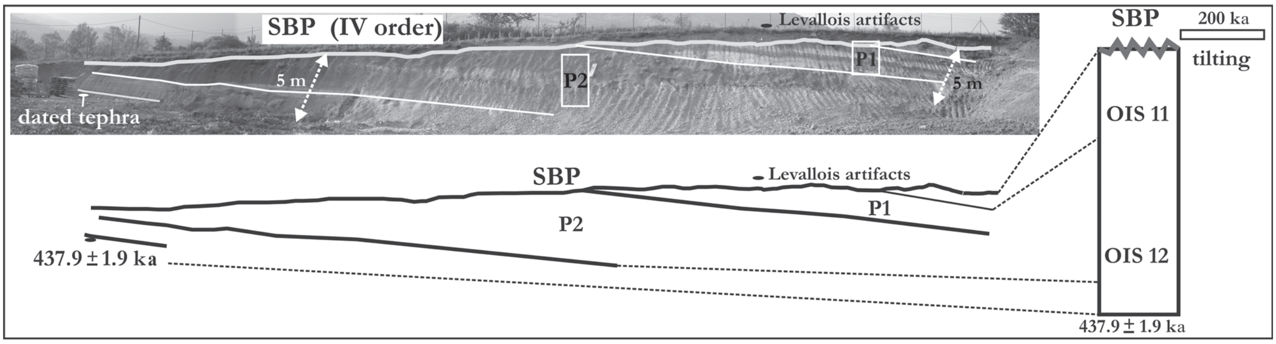

Fig. 5. Chronostratigraphic scheme of the uppermost portion of the Sessano infilling. The soil profiles (P1 and P2) and related micro-morphological characters are showed in Fig. 6. On the basis of the dated tephra layer (437.9±1.9 ka BP, outcropping at the base of the soil profiles, and on the basis of the Levallois artifacts (200 ka BP), discovered at the top of the soil profiles, the P1 and P2 paleosols can be referred to Oxigen Isotopic Stage 12 (OIS 12) and 11 (OIS 11, respectively).

these surfaces, the SBP, located in the central-northern part of the basin at 700 m a.s.l., provided very important chronostratigraphic constraints through the analysis of tephra layers, pollen and paleosols interbedded in the upper part of the Middle Pleistocene fluvio-palustrine succession (Fig. 5). Along the borders of the adjacent Carpino Basin, this order is represented by remnants at about 600 m a.s.l. and lying at about 100 m above the plain. They cut both the pre-Quaternary bedrock and the Quaternary deposits. Measurements of the local gradients characterizing the paleosurfaces of the Sessano and Carpino areas support their correlation and allow them to be referred to a generic Middle Pleistocene Tyrrhenian dipping paleolandscape (Di Bucci et al. 2002 and Amato et al. 2010).

Other paleosurfaces (below 500 m a.s.l.)

Other relicts of erosional and depositional surfaces are present in the study area below 500 m a.s.l. They were ascribed to the Middle Pleistocene by Brancaccio et al. (2000) and Coltorti et al. (2005). Such surfaces generally represent stripped fluvial terraces hanging a few tens of meters over the valley floors; they are mainly located in the upper part of the Volturno River catchment area. It is difficult to give these surfaces a regional significance (according to the criteria of Widdowson 1993) due to their limited presence in the upper-middle Volturno Basin which prevents any correlation with the surfaces located along the valley flanks of the Trigno and Biferno Rivers. The Volturno surfaces were generated by the interaction between the local tectonic and the Late Quaternary climatic fluctuations (Brancaccio et al. 2000; Coltorti et al. 2005). They probably developed after the formation of the IV order of paleosurfaces or could represent the remnants of tectonically lowered IV order paleosurfaces.

Morphochronological constraints from the Sessano-Carpino area

As previously described, all the recognized orders of paleosurfaces are present within the Sessano-Carpino area, alternatively cut into carbonate and/or siliciclastic rocks, or in Quaternary deposits (Fig. 3). Thanks to this circumstance and the fact that the Sessano Basin features a well-dated Middle Pleistocene filling, the Sessano-Carpino area is a key site to understand the tectonic and related geological evolution of the Molise Apennine.

Chronostratigraphic data

In the Sessano Basin, a Middle Pleistocene pedosedimentary fill provides important evidence on paleoenvironmental, climatic and tectonic events that governed its evolution and extinction. These features were investigated in detail using an integrated archaeo-tephro-stratigraphic, palynological and pedological approach. The uppermost part of the fill, ca. 11 m thick, crops out along the scarps of several artificial trenches. It is made up of parallel sand, clay and soil layers, often separated by abrupt boundaries, indicating discontinuous fluvial and marshy sedimentation alternating with soil formation and erosional phases. This succession is characterized by the presence of abundant volcaniclastic material which is generally reworked, except for a 35 cm-thick primary tephra layer which crops out at its base (Fig. 5) and mainly consists of white pumices (Ø max = 1 cm). The outcropping portion of the fill is characterized by a N6°E strike and a strata dip of 17 degrees toward east (Fig. 5). It is locally affected by high-angle faults with vertical throws not exceeding 0.3 m. This tectonic phase occurred before the planation phase which shaped the IV order SBP, the latter being cut into the tilted succession.

The chronological position of this uppermost portion of the Sessano infill is clearly established by the $^{40}Ar/^{39}Ar$ age of the tephra layer that outcrops at its base (437 ± 1.9 ka; Russo Ermolli et al. 2010). Chemical analysis by Russo Ermolli et al. (2010) allowed its correlation with the High Potassium Series (HKS) explosive volcanic activity of the Roccamonfina volcano, namely with the Rio Rava Plinian eruption, dated by Rouchon et al. (2008) to 439 ± 9 ka. Another important chronological constraint is represented by the discovery, at the top of the SBP, of various Paleolithic artefacts ascribed to the Levallois Culture (A. Minelli, Molise University, personal communication). Their age of ca. 200–150 ka indicates that the extinction of the paleomarsh, the tilting of the sedimentary succession and the genesis of the SBP occurred after 437 ka and before 200 ka.

Paleopedological and pollen data

The pedostratigraphic succession overlying the dated tephra layer was subdivided into two soil profiles, P1 and P2, repre-

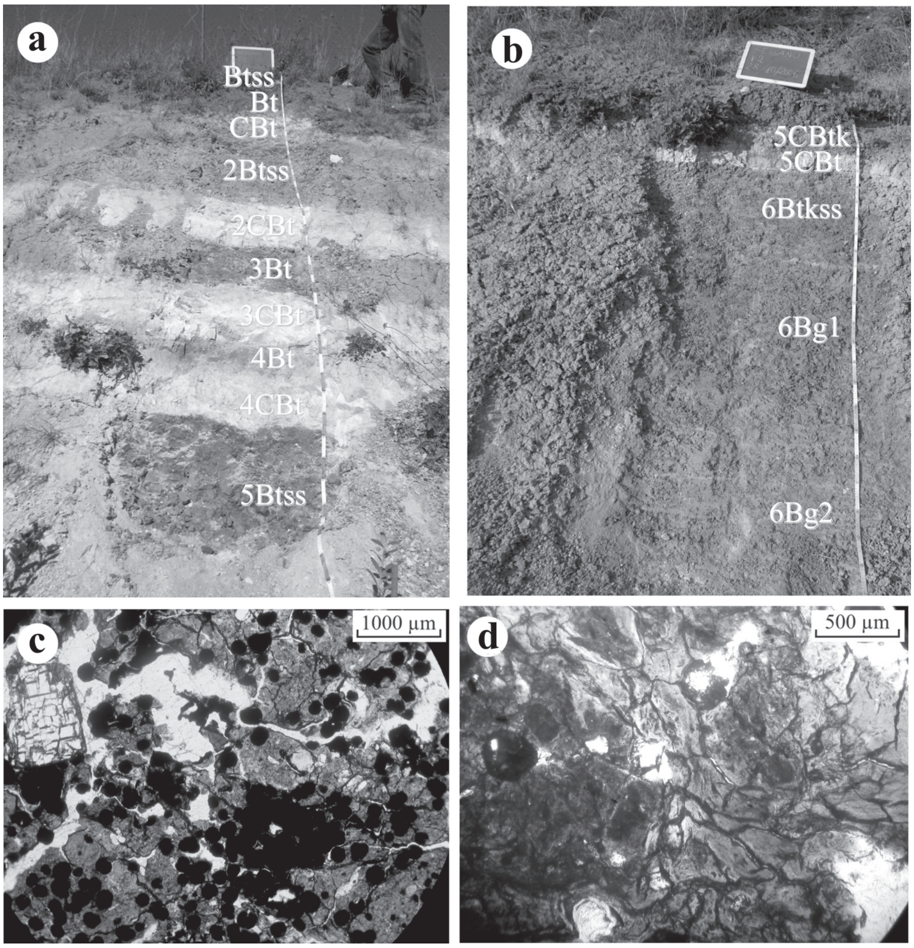

Fig. 6. Pedostratigraphic succession of the uppermost portion of the Sessano infill subdivided into soil profiles P1 (**a**) and P2 (**b**) and micrographs in plane polarized light of Fe-Mn segregations from horizon 2Btss (**c**) and clay coatings from horizon Bt (**d**). For location see Fig. 5.

senting its upper and lower portion, respectively (Figs. 5, 6a and b). The reworked volcaniclastic ash layers represent CBt horizons, white to greyish in colour, alternating with well-structured, brown to yellow and yellowish-brown buried soils (B horizons). In particular, above the basal soil horizons (Bg) showing redox concentrations (pseudogley, i.e. temporary hydromorphic features; IUSS Working Group WRB, 2006; Soil Survey Staff, 2010) there is a series of argillic (Bt) horizons with illuvial clay coatings, also showing other distinct genetic features: various horizons (Bss) at different stratigraphic depths exhibit vertic properties (shiny faces and slickensides due to shrink-swell dynamics), whereas intermediate horizons are characterized by calcium carbonate concretions (Bk). Preliminary SEM-EDS microprobe analyses were performed on vesicular glass fragments (subangular micropumices, 30 to 400 µm in size) identified in two ash layers (horizons CBt and 4CBt) in the upper and lower portion of the succession. Glass shards show a trachytic composition (with a dispersal of data towards the phonolite field), which is not so dissimilar from those analysed and dated in the underlying core succession (Russo Ermolli et al. 2010). These results suggest the same provenance and a cyclical reworking of the same tephra products within the basin infill, as supported by sedimentary evidence, where the dominant trachytic over phonolitic composition may indicate a decrease in alkali as a consequence of chemical weathering and leaching. Besides, the later HKS products of other Middle Pleistocene explosive eruptions from the Roccamonfina volcano (cf. Rouchon et al. 2008) should also be taken into account.

With the aid of micromorphological analysis of thin sections obtained from undisturbed soil samples, coupled with the field features, the main environmental conditions throughout the pedostratigraphic succession may be assessed. What emerges is, on the whole, a rather humid environment. However, some changes can be identified from bottom to top, with an overall trend from moderately humid to slightly drier conditions followed, in turn, by more humid conditions. In particular, in soil profile P2 a poorly-drained (marshy) humid environment is indicated at the base by its redoximorphic features, with some seasonal contrast and further dryness. This is also indicated in the upper horizons by vertic features, moderate clay translocation, the latter being typical of Quaternary interglacials or mild interstadials within glacial periods in mid-latitude areas (e.g. Catt 1989; Kemp et al. 2004; Scarciglia et al. 2006), and secondary $CaCO_3$ precipitation. The modest extent of clay illuviation, the occurrence of carbonate concretion and the complete lack of rubification better support drier (and possibly colder) conditions of glacial phases rather than interglacials. A progressive return to more humid conditions is clearly shown in soil profile P1 and mainly in its upper horizons, where a weak change to a redder hue (10YR) of the matrix is observed, coupled with many reddish-black iron-manganese segregations (Fig. 6c). The very abundant laminated clay coatings (different generations), observed in thin sections (Fig. 6d), suggest a clear transition towards warm and humid (interglacial-like) climatic conditions.

Pollen analysis of the trench section (Fig. 5) was not successful, since all the collected samples were barren or very poor in pollen (with a very advanced state of oxidation towards the top of the succession), only allowing a qualitative approach to be adopted. Some considerations can nevertheless be attempted on the basis of the pollen data from the underlying cored succession where two climatic cycles were recognized and ascribed to Oxygen Isotope Stages (OIS) 15 to 12 (Russo Ermolli et al. 2010). The warm and humid period recognized in the upper part of the core (OIS 13) shows a transition towards a subsequent glacial period which is announced by the decline in deciduous forest elements. This deteriorating climatic trend seems confirmed by the qualitative analysis of the trench samples where a dominance of herbaceous elements is documented. Therefore, at least the base of the trench section of Fig. 5 should record the glacial stage 12 which represents, together with stage 16, the most severe cold period of the Middle and Late Pleistocene (Lisiecki & Raymo 2005). This glacial period has never been fully recognized in Italian pollen records. A few levels at Vallo di Diano and Acerno, in the southern Apennines, were doubtfully ascribed to OIS 12 on the basis of climatostratigraphy (Russo Ermolli & Bertini 2009) and tephrostratigraphy (Di Donato et al. 2009), respectively.

In synthesis, the main environmental changes depicted in the two soil profiles of the trench section highlight a transition from moderately humid (lower soil profile P2) to slightly drier and colder conditions (upper soil profile P2 to lower P1), followed by warmer and more humid conditions (upper soil profile P1). Similar evidence is indicated by pollen data, which are the image of a glacial period at the base of the trench section, following a deterioration trend recorded towards the top of the underlying core stratigraphy. Soil features show that this glacial period is followed by a possible further climatic amelioration. According to the above chronostratigraphic position, the soil and pollen analyses of the trench section suggest that this portion of the Sessano infill probably recorded a later interglacial imprint (possibly OIS 13) or an interstadial phase during OIS 12, followed by full glacial conditions in the intermediate portion (OIS 12), up to real interglacial conditions towards the top, presumably related to the subsequent OIS 11.

Discussion

Given the above morphostratigraphic and chronological data the main morphosedimentary changes recorded in the uppermost portion of the Sessano fill may reasonably be attributed to the Middle Pleistocene, in particular to OIS 12 and OIS 11 (Fig. 5). After this period, a phase of extensional tectonics, acting on N-S oriented faults, caused the E-SE tilting of the Sessano succession and the extinction of the paleomarsh (Amato et al. 2010). The truncation of the previously tilted succession and the formation of the Tyrrhenian-ward dipping IV order paleolandscape (SBP) started immediately after.

We believe that this phase of paleosurface formation, which is clearly constrained to the period between 437.9 ± 1.9 ka and 200 ka (see section: Morphochronological constraints from the Sessano-Carpino area — Chronostratigraphic data), can be even better defined in chronological terms on the basis of the following considerations:

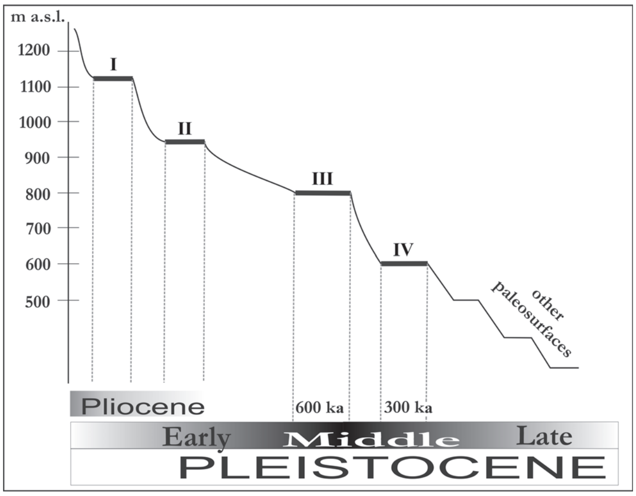

Fig. 7. Morphostratigraphic and chronological sequence of the Molise Apennine paleosurfaces.

● The tephra layer dated to 438 ka is overlain by 11 m of fluvio-marshy and volcaniclastic deposits alternating with several paleosols. Both the discontinuous sedimentation and the development of soils correspond to an additional time span that may include one or more climatic cycles (from the end of OIS 12 to OIS 11). This is also supported by the main changes in soil features (and related environmental conditions) along the pedostratigraphic succession, coupled with the dominance of herbaceous pollen taxa and their severe state of oxidation towards the top.

● After this additional time interval, tectonic deformation (tilting) occurred, which corresponds to another time interval to be added before the genesis of the SBP surfaces within the Sessano Basin. Also this time interval may have covered one or more climatic cycles, from the end of OIS 11 onwards. We cannot exclude the occurrence of further exposure of the paleosurface to pedogenetic processes after the extinction of the above pedosedimentary cycle and its tectonic deformation during more recent times. In fact, the abundant clay coatings of surface soil horizons (in profile P1) may have been superimposed throughout various interglacials younger than OIS 11 (OISs 9 to 7 or 5). Another major erosion surface is indicated by the truncation of the upper paleosol in question, as highlighted by the lack of organic-mineral or albic horizons and the exposure of typical deep (argillic) ones at the topographic surface (Kemp et al. 2004; Robustelli et al. 2009).

On the basis of these considerations, the beginning of the planation phase leading to SBP formation can be chronologically constrained to a time interval that spans from ca. 350 to ca. 300 ka, in agreement with the age of the Carpino Basin infill (Di Bucci et al. 2002).

Conclusions

The chronostratigraphic data obtained for the SBP surface represent a new morphochronological marker for the Molise Apennine: they are the first *ante quem* and *post quem* dates, and enable the evolution of the Molise Apennines to be better defined. In synthesis, the IV order paleosurfaces can be ascribed to the Middle Pleistocene, and most likely to the time interval spanning from 350 to 300 ka.

Using this chronological marker, supported by data from the literature, we were able to fix some further temporal thresholds to the various orders of paleosurfaces identified in the Molise Apennines (Fig. 7). The III order paleosurfaces are part of a paleolandscape already hanging above the fluvio-lacustrine Sessano Basin before its extinction and then before 438 ka. Within the Boiano Basin, the paleosurface that cuts the San Massimo lacustrine deposits, located at ca. 800 m a.s.l., post-dates the top of the deposits that are dated to ca. 600 ka. It is therefore representative of a paleolandscape that evolved during the Middle Pleistocene between 600 and 350 ka.

No chronological data are available for the I and II orders of paleosurfaces. However, morphostratigraphic regional correlations, the presence of Upper Miocene flysch deposits cropping out on top of the Montagnola di Frosolone massif and the total lack of Pliocene deposits in the whole area may suggest that the genesis of these orders most likely occurred between the Early Pliocene and the Early Pleistocene, in agreement with what is known for other sectors of the Apennine chain (e.g. *Paleosuperficie Auct.*, Brancaccio et al. 1986; Ascione & Cinque 1999, 2003). On the other hand, given the age of the IV order of paleosurfaces, the other paleosurface remnants of local significance, located at altitudes below 500 m a.s.l., must have been generated after 300 ka from the interplay between local tectonic and Late Quaternary climatic fluctuations.

In conclusion, the results of our study show that a multidisciplinary approach integrating several tools and analytical techniques can be successfully applied to obtain important and reliable data for reconstructing landscape evolution in a young orogenic chain.

References

Amato A. 2000: Estimating Pleistocene tectonic uplift rates in the Southeastern Apennines (Italy) from erosional land surfaces and marine terraces. In: Slaymaker O. (Ed.): Geomorphology, human activity and global environmental change. *John Wiley & Sons*, 67–87.

Amato A. & Cinque A. 1999: Erosional landsurfaces of the Campano-Lucano Apennines: genesis, evolution and tectonic implications. *Tectonophysics* 315, 251–267.

Amato V., Aucelli P.P.C., Cesarano M., Pappone G., Rosskopf C.M. & Russo Ermolli E. 2010: Quaternary evolution of the Molise Apennine (southern Italy): new constraints from the Sessano intra-mountain basin. *Geomorphology*, submitted.

Antonucci A., De Corso S., Di Luzio E., Lenci F., Sansonne P., Scrocca D. & Tozzi M. 2000: The Montagnola di Frosolone and the northern Matese massif: new data on the Molise geology. *Boll. Soc. Geol. Ital.* 119, 637–654 (in Italian).

Ascione A. & Cinque A. 1999: Tectonics and erosion in the long term relief history of the Southern Apennines (Italy). *Z. Geomorphology N.F. Suppl.-Bd.* 118, 1–16.

Ascione S. & Cinque A. 2003: Geomorphological changes driven by recent tectonics in southern Apennines. *Quaternario, Ital. J. Quat. Sci.* 16, 1, 133–140 (in Italian).

Bartolini C. 1999: An overview of Pliocene to present-day uplift and denudation rates in the Northern Apennines. In: Smith B.J., Whalley W.B. & Warke P.A. (Eds.): Uplift, erosion and stability: Perspective on long-term landscape development. *Geol. Soc. London*, *Spec. Publ.* 162, 119–125.

Bartolini C., D'Agostino N. & Dramis F. 2003: Topography, exhumation and drainage network evolution of the Apennines. *Episodes* 26, 3, 212–216.

Basili R., Galadini F. & Messina P. 1999: The application of palaeolandsurface analysis to the study of recent tectonics in central Italy. In: Smith B.J., Whalley W.B. & Warke P.A. (Eds.): Uplift, erosion and stability: perspectives on long-term landscape development. *Geol. Soc. London*, *Spec. Publ.* 162, 109–117.

Boenzi F., Capolongo D., Cecaro G., D'Andrea E., Giano S.I., Lazzari M. & Schiattarella M. 2004: Poliphasic geomorphological evolution and rising rates on the south-western margin of the Val d'Agri (southern Apennines). *Boll. Soc. Geol. Ital.* 123, 357–372 (in Italian).

Bosi C. 2002: Interpretation of relict surfaces in central Apennines: the Colfiorioto zone case (Perugia and Macerata region). *Quaternario, Ital. J. Quat. Sci.* 15, 69–82 (in Italian).

Bosi C., Caiazzo C., Cinque A. & Messina P. 1996: Relict surfaces in the fucese area (central Apennines) and their possible meaning in the geological reconstruction. *Quaternario, Ital. J. Quat. Sci.* 9, 1, 381–386 (in Italian).

Brancaccio L. & Cinque A. 1988: Geomorphologic evolution of the Campano-Lucano Apennine. *Mem. Soc. Geol. Ital.* 41, 135–136 (in Italian).

Brancaccio L., Sgrosso I., Cinque A., Orsi G., Pece R. & Rolandi G. 1979: Residual patches of Pleistocene lacustrine sediments on the norther slope of the Matese massif (S. Massimo). *Boll. Soc. Nat. Napoli* 88, 275–286 (in Italian).

Brancaccio L., Cinque A. & Sgrosso I. 1986: Inherited morpho-structural elements in the central-southern Apennine landscape. *Boll. Soc. Geol. Ital.* 35, 869–874 (in Italian).

Brancaccio L., Di Crescenzo G., Rosskopf C.M., Santangelo N. & Scarciglia F. 2000: Geological map of Quaternary deposits and geomorphological map of the Volturno river valley (Molise, southern Italy). Descriptive notes. *Quaternario, Ital. J. Quat. Sci.* 13, 1–2, 81–94 (in Italian).

Burbank D.W. & Anderson R.S. 2001: Tectonic geomorphology. *Blackwell Science*, Malden, Massachusetts, 1–274.

Catt J.A. 1989: Relict properties in soils of the central and north-west European temperate region. *Catena,* Suppl. 16, 41–58.

Cinque A., Patacca E., Scandone P. & Tozzi M. 1993: Quaternary kinematic evolution of the Southern Apennines. Relationship between surface geological features and deep lithospheric structures. *Ann. Geof.* 36, 249–260.

Coltorti M. & Pieruccini P. 2000: A late Lower Pliocene planation surface across the Italian Peninsula: a key tool in neotectonic studies. *J. Geodyn.* 29, 323–328.

Coltorti M., Ferand G., Marzoli A., Peretto C., Ton That T., Voinchet P., Bohain J.J., Minelli A. & Thun Hohenstein U. 2005: New $^{40}Ar/^{39}Ar$, stratigraphic and palaeoclimatic data on the Isernia La Pineta Lower Palaeolithic site, Molise, Italy. *Quat. Int.* 131, 11–22.

Corrado S., Di Bucci D., Naso G. & Butler R.W.H. 1997a: Thrusting and strike-slip tectonics in the Alto Molise region (Italy): implications for the Neogene-Quaternary evolution of the Central Apennine orogenic system. *J. Geol. Soc. London* 154, 679–688.

Corrado S., Di Bucci D., Leschiutta I., Naso G. & Trigari A. 1997b: Quaternary tectonics of the Isernia plain in the structural evolution of the Molise sector. *Quaternario, Ital. J. Quat. Sci.* 10, 2, 609–614 (in Italian).

Corrado S., Di Bucci D., Naso G. & Valensise G. 2000: The role of pre-existing structures in Quaternary extensional tectonics of the Southern Apennines, Italy: the Boiano Basin case history. *J. Czech Geol. Soc.* 45, 3/4, 217.

D'Alessandro L., Miccadei E. & Piacentini T. 2003: Morphostructural elements of central-eastern Abruzzi: contributions to the study of the role of tectonics on the morphogenesis of the Apennine chain. *Quat. Int.* 101–102, 115–124.

Di Bucci D., Corrado S. & Naso G. 2002: Active faults at the boundary between Central and southern Apennines (Isernia, Italy). *Tectonophysics* 359, 47–63.

Di Bucci D., Naso G., Corrado S. & Villa I.M. 2005: Growth, interaction and seismogenetic potential of coupled active normal faults (Isernia Basin, central-southern Italy). *Terra Nova* 17, 44–55.

Di Donato V., Russo Ermolli E. & Di Pasquale G. 2009: Vegetation and climate changes during the OIS 9–8 from Compositional Data Analysis and Modern Analogues Technique of the high resolution pollen record of Acerno (southern Italy). *AIQUA-AIGEO Workshop* "Climatic variability in Quaternary times: the Italian research". Rome, 18–20 February 2009.

England P. & Molnar P. 1990: Surface uplift, uplift of rocks, and exhumation of rocks. *Geology* 18, 1173–1177.

Gioia D. & Schiattarella M. 2006: Morpho-tectonic characters of the Valico Pratesi and Lauria Mts areas (southern Apennines). *Quaternario, Ital. J. Quat. Sci.* 19, 129–142 (in Italian).

IUSS Working Group WRB 2006: World reference base for soil resources 2006 — a framework for international classification, correlation and communication. *World Soil Resources Report* 103, FAO, Rome, 1–132.

Kemp R.A., King M., Toms P., Derbyshire E., Sayago J.M. & Collantes M.M. 2004: Pedosedimentary development of part of a Late Quaternary loess-palaeosol sequence in northwest Argentina. *J. Quat. Sci.* 19, 6, 567–576.

Lisiecki L.E. & Raymo M.E. 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleocean.* 20, PA1003. doi:10.1029/2004PA001071.

Ollier C. & Pain C. 1996: Regolith, soils and landforms. *John Wiley & Sons*, New York, 1–316.

Patacca E., Scandone P., Bellatalla M., PerilliI N. & Santini U. 1992: The junction zone between northern and southern Apennine arch in Abruzzo and Molise. In: Tozzi M., Cavinato G.P. & Parotto M. (Eds.): Preliminary studies in the data capture from profile CROP 11 Civitavecchia-Vasto. *St. Geol. Camerti, Vol. Spec*. 1991/2, 417–441 (in Italian).

Robustelli G., Lucà F., Corbi F., Pelle T., Dramis F., Fuselli G., Scarciglia F., Muto F. & Cugliari D. 2009: Alluvial terraces on the Ionian coast of northern Calabria, southern Italy: implications for tectonic and sea level controls. *Geomorph.* 106, 165–179.

Rouchon V., Gillot P.Y., Quidelleur X., Chiesa S. & Floris B. 2008: Temporal evolution of the Roccamonfina volcanic complex (Pleistocene), Central Italy. *J. Volcanol. Geoth. Res.* 177 (2008) 500–514.

Russo Ermolli E. & Bertini A. 2009: L'enregistrement pollinique des cycles de 100 ka en Italie: reconstitution des paléoenvironnements et valeur stratigraphique des taxons exotiques. *Séance spécialisée SGF-AFEQ* « Paléoenvironnements et paléoclimats européens du Pléistocène inférieur et moyen », Paris, 3 décembre 2009 (in French).

Russo Ermolli E., Aucelli P.P.C., Di Rollo A., Mattei M., Petrosino P., Porreca M. & Rosskopf C.M. 2010: An integrated stratigraphical approach to the late Middle Pleistocene succession of the Sessano lacustrine basin (Molise, Italy). *Quat. Int.* 225, 114–127.

Scarciglia F., Pulice I., Robustelli G. & Vecchio G. 2006: Soil chronosequences on Quaternary marine terraces along the northwestern coast of Calabria (Southern Italy). *Quat. Int.* 156–157, 133–155.

Schiattarella M., Di Leo P., Beneduce P. & Giano S.I. 2003: Quaternary uplift vs tectonic loading. A case-study from the Lucanian Apennine, southern Italy. *Quat. Int.* 101–102, 239–251.

Schiattarella M., Di Leo P., Beneduce P., Giano S.I. & Martino C. 2006: Tectonically driven exhumation of a young orogen: An example from the southern Apennines, Italy. *Geol. Soc. Amer., Spec. Pap*. 2006, 398, 371–385.

Scrocca D. & Tozzi M. 1999: Mio-Pliocene tecto-genesis of Molise Apennine. *Boll. Soc. Geol. Ital.* 118, 2, 255–286 (in Italian).

Soil Survey Staff 2010: Keys to Soil Taxonomy, 11th edit. *USDA-Natural Resources Conservation Service*, Washington DC, 1–338.

Summerfield M.A. 1991: Global geomorphology. *Longman Scientific and Technical*, Harlow, 1–537.

Watchman A.L. & Twidale C.R. 2002: Relative and absolute dating of land surfaces. *Earth Sci. Rev.* 58, 1–49.

Westaway R. 1993: Quaternary uplift of southern Italy. *J. Geophys. Res*. 98, 741–772.

Widdowson M. 1997: The geomorphological and geological importance of paleosurfaces. In: Widdowson M. (Ed.): Paleosurfaces: recognition, reconstruction and palaeoenvironmental interpretation. *Geol. Soc. London*., *Spec. Publ*. 120, 1–12.