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Long-term landscape evolution of the Molise sector of the central-southern Apennines, Italy

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Abstract: This paper concerns the reconstruction of the main stages of the long-term landscape evolution of the Molise portion of the central-southern Apennines along a transect divided into three sectors (SW, Central and NE). Analysis mainly focused on geomorphological, stratigraphical and structural data supported by chronological constraints, coming from an overall review of past literature and several studies carried out by the authors of the paper during the last 20 years. The results obtained allowed the elaboration of a conceptual model of the long-term evolution of the Molise sector of the central-southern Apennines. Starting from the Pliocene, the emersion of the Molise area occurred gradually from SW to NE, allowing a polycyclic landscape to evolve under the major controls first of compression then transtensional to extensional tectonics as well as climatic variations. Principal markers of the Quaternary geomorphological evolution of the Molise area are represented by the infill successions of the intermontane tectonic depressions located in its internal, SW sector and by four orders of palaeosurfaces that developed between the Early Pleistocene and the beginning of the Late Pleistocene across the region. These markers testify to the alternation of phases of substantial tectonic stability and uplift whose spatial-temporal distribution could be assessed along the investigated transect. Results highlight that the most important stages of landscape evolution occurred during the Early and Middle Pleistocene. At the beginning of the Late Pleistocene, the Molise sector of the Apennine chain had already reached its present setting and further landscape evolution occurred under the major control of climate and land-use.

Keywords: young orogen, tectonics, Apennine chain, geomorphological evolution, palaeolandscape, chronostratigraphy, Plio–Pleistocene.

Introduction

The Molise region is located in the axial and external sectors of the junction zone between the central and southern Apennine chains (Fig. 1). This region is characterized by diversified landscapes mainly constituted by high mountain areas (up to 2000 m), hilly environments, intermontane basins, river valleys and alternating high coast and alluvial coastal plain sectors (Fig. 1). Each of these landscapes presents different morphological and geological-structural features in terms of both surface and deep structure, reflecting an individual Quaternary morphogenesis and evolution.

Studies concerning landforms and their post-orogenic morphological evolution are generally very complex and require an interdisciplinary approach that primarily involves geomorphology, field and structural geology and chronostratigraphy, and must give due consideration to Quaternary post-orogenic tectonic events that occurred in the central and southern Apennine chain.

For the Apennines that are one of the youngest mountain chains in the world, these approaches have been successfully applied in several sectors of the central and southern Apennines (Brancaccio et al. 1979, 1988, 2000; Bosi et al. 1996; Amato & Cinque 1999; Coltorti & Pieruccini 2000; Bartolini et al. 2003; D'Alessandro et al. 2003; Schiattarella et al. 2003, 2006; Coltorti et al. 2005; Di Bucci et al. 2005; Aucelli et al. 2011; Amato et al. 2014; Gioia et al. 2014). With particular reference to the Molise sector of the Apennines, several studies have been conducted and published by our research group (Aucelli et al. 2001, 2010, 2011, 2012, 2013, 2014; Russo Ermolli et al. 2010; Amato et al. 2011, 2012, 2013, 2014; Bracone et al. 2012a), while others are still in progress.

Particularly, the internal, south-western sector of the Molise region, including the Matese, Montagnola di Frosolone and Venafro mountains (Aucelli et al. 2001, 2010, 2012, 2013; Cesarano et al. 2011) and the intermontane basins of Boiano, Venafro, Sessano and Isernia (Amato et al. 2011, 2012, 2013, 2014; Aucelli et al. 2014), has been investigated in great detail (Fig. 1). Instead, the central sector, which is located between the NE slope of the Montagnola di Frosolone and the Frentani Mountains (Fig. 1), has been much less studied, apart from some geological (Lanzafame & Tortorici 1976; Vezzani et al. 2004, 2010) and geomorphological study (Aucelli et al. 2001, 2010). Finally, the north-eastern, coastal sector was mainly investigated first for petroleum research (Casnedi et al. 1981, 1982; Cello et al. 1989), then subsurface stratigraphic

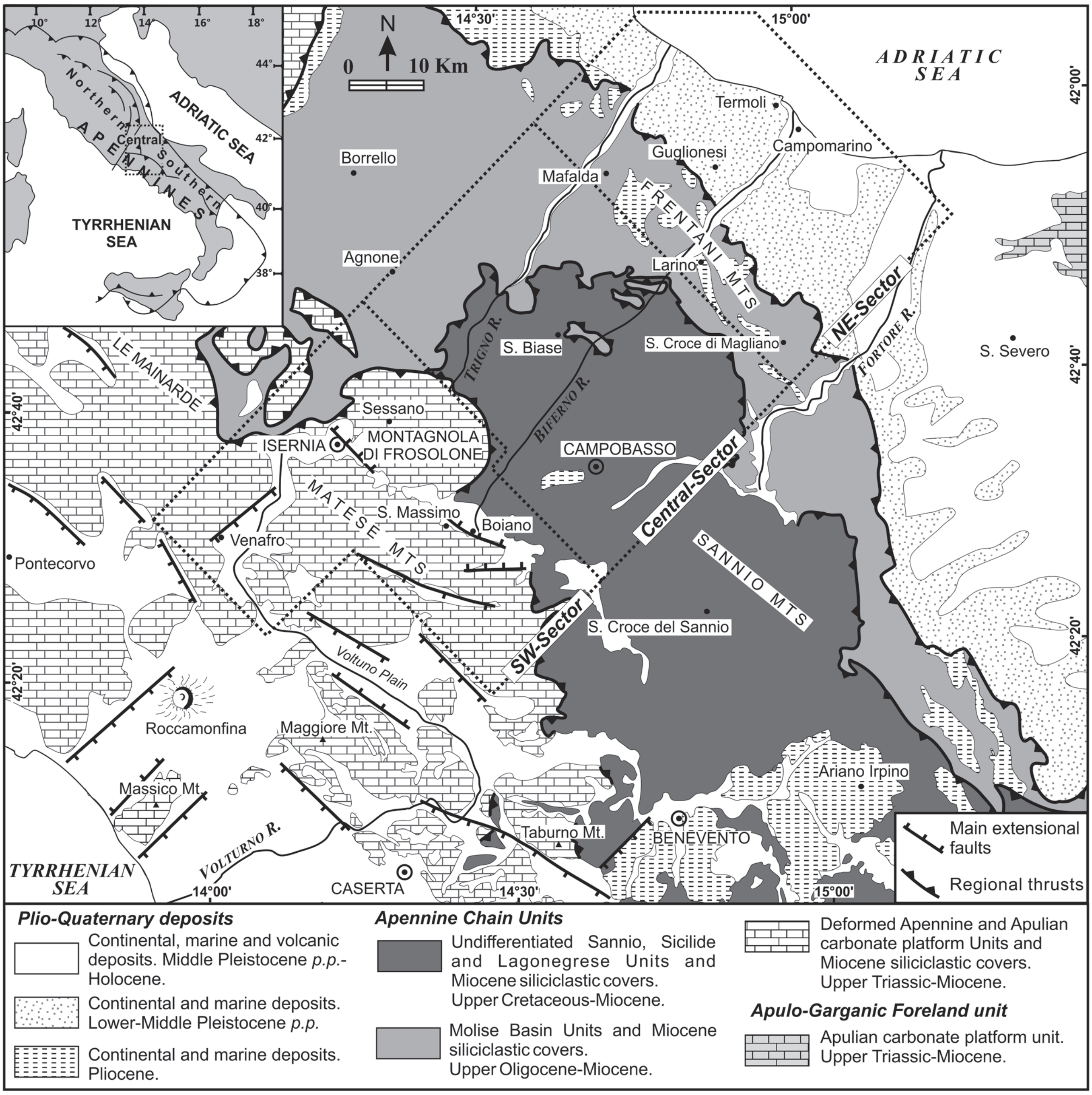


Fig. 1. Geological sketch map showing the distribution of the main tectonic units and Pliocene–Quaternary deposits in the Campania–Molise portion of the central-southern Apennines.

characterization of the Pliocene–Pleistocene successions (Amorosi et al. 2009, 2016; Bracone et al. 2012a, b) and, finally, in relation to the genesis and evolution of the alluvial plains of the Trigno and Biferno rivers (Aucelli et al. 2001; Frezza et al. 2012; D'Amico et al. 2013; Rosskopf & Scorpio 2013; Amorosi et al. 2016).

Available studies to date are integrated by recent, mostly unpublished geological data acquired during regional field surveys (Vezzani et al. 2004) and the CARG (Geological CARtoGraphy) projects (geological maps "Campobasso", "Trivento" and "Vasto") (ISPRA 2010; Pappone et al. 2010; Calamita et al. 2011; ISPRA 2011a, b; Sgrosso & Naso 2011) that add important new knowledge on the regional tectono-stratigraphic setting of the study area.

However, while these studies clarify the main phases of the stratigraphical and geomorphological evolution of several sectors of the Molise Apennine, they do not address the comparison and correlation between different sectors.

The main objectives of the present paper are to order and link data coming from different sectors of the Molise Apennine and to fill major gaps in knowledge on its long-term evolution. For this purpose, a review and integrated analysis of mainly geomorphological, stratigraphical, structural and geo-chronological data (Ar/Ar dating and tephrostratigraphy on tephra layers interbedded with the Quaternary successions, palaeomagnetism, palynology) was carried out. The results obtained have allowed us to propose for the first time a model of the long-term landscape evolution of the Molise sector of the Apennine chain. In particular, the main phases of the tectonic and long-term geomorphological evolution of the Molise Apennines since the Pliocene are detailed along a study transect that crosses the Molise region, from the Matese Massif to the Adriatic coast (Fig. 1).

Geological and geomorphological setting

The Molise portion of the central-southern Apennines, thanks to its diversified geological and morphostructural features, can be divided into three sectors: a south-western, a central and a north-eastern sector (hereinafter also named SW Sector, Central Sector and NE Sector) (Fig. 1).

The SW Sector is dominated by Meso–Cenozoic carbonate platform and slope-basin units (respectively the Matese and Montagnola di Frosolone units) and, to a lesser extent, by upper Miocene siliciclastic foredeep deposits (Molise Flysch, Pappone et al. 2010) overlying the carbonate units. This sector is dominated by a mountainous landscape with high mountain areas including major peaks between 1800 and 2000 m a.s.l., and hosts several intermontane basins with floors located between 300 and 700 m a.s.l. The Central Sector is located between the north-eastern slope of the Montagnola di Frosolone and the Frentani Mountains and characterized by a typical hilly morphology, mainly developed on clayey-marly limestone successions and siliciclastic deposits belonging to the Sannio and Molise basin units. The Upper Cretaceous–Miocene Sannio basin units (originally located to the west of the Apennine carbonate platform, Patacca et al. 1992) overlapped, after the Early Messinian, both the Apennine carbonate platform units and the Molise basin units (Cesarano et al. 2011). The Molise units (Upper Oligocene–Miocene) refer to the basin domain (Molise basin) that separated the Apennine carbonate platform domain (Matese-Montagnola di Frosolone) to the west from the Apulian carbonate platform domain to the east, and are made of three distinct tectonic units, namely Agnone, Tufillo and Daunia (*sensu* Patacca et al. 1992). The Tufillo and Daunia units largely consist of calcareous turbiditic successions of Burdigalian–Tortonian age (Lirer et al. 2007) that are widespread in the northern and eastern portions of this sector and appear in the San Biase area in tectonic windows beneath the Sannio units (Fig. 1). The Daunia Unit, which represents the outer portions of the Molise basin, is covered by Pliocene deposits of a wedge-top basin that are represented by the Tona Formation (Boni et al. 1969).

Finally, the NE Sector, which stretches between the Frentani Mountains and the Adriatic coast, is dominated by sedimentary successions made up of clays, sandstones and conglomerates from marine and continental environment. These successions form a Pliocene (Piacenzian p.p.)–Pleistocene (Gelasian–Ionian) regressive cycle (Bracone et al. 2012b and references therein) made up, from the bottom to the top, by the Montesecco Clays, Serracapriola Sands and Campomarino Conglomerates with the latter being divided into two distinct sedimentary cycles (Bracone et al. 2012b). This sector is characterized by a low relief energy and regular morphology dominated by NNW–SSE oriented terraced ridges gently sloping toward the Adriatic coast and the interposed alluvial coastal plains of the Trigno and Biferno rivers.

The current geological setting of the Molise sector of the central-southern Apennines is the result of a complex tectonic evolution that started in the Middle–Late Miocene (Patacca et al. 1990; Patacca & Scandone 2007 and references therein) and was characterized by coeval east and north-eastward thrust stacking during the migration of deformation toward the Apulian foreland and by hinterland extension due to the opening of the Tyrrhenian back-arc basin (Channell et al. 1979; Malinverno & Ryan 1986; Patacca et al. 1990; Hippolyte et al. 1994; Mazzoli et al. 2000). These geodynamic processes were driven by the passive sinking rollback of the Adriatic-Ionian lithosphere (Malinverno & Ryan 1986). The Apennine accretionary prism gradually incorporated the tectonostratigraphic units derived alternatively from the carbonate platform and basin domains of Mesozoic–Cenozoic age (D'Argenio et al. 1973; Mostardini & Merlini 1986). The timing of orogenic migration toward the east was constrained by the dating of thrust-top and foredeep basin deposits which gradually formed (Casero et al. 1988; Patacca et al. 1990, 1992; Cipollari & Cosentino 1995). The compressional phases produced a significant shortening of the accretionary prism that occurred through a thin-skinned deformation (e.g., Mostardini & Merlini 1986; Marsella et al. 1995; Doglioni et al. 1996; Mazzotti et al. 2000; Patacca & Scandone 2001; Patacca et al. 2007; Scrocca 2010).

Starting from the Early Pliocene, the entire stack of thrust sheets was already superimposed on the inner edge of the Apulian platform. The latter, however, underwent shortening processes through the formation of duplex structures (Mostardini & Merlini 1986) only in the Middle–Late Pliocene. The deformation of the buried Apulian Platform unit produced in some cases the development of breaching thrusts that cut the original roof-thrust, leading to the formation of out-of-sequence within the roof unit and consequently localized uplift of the accretionary prism.

Within the Pliocene and Pleistocene *p.p.* interval (from 3.6 to 1.4 My), the development of wedge-top basins characterized by shallow marine environments occurred on the thrust sheets (Ascione et al. 2012). Starting from the Early Pleistocene, the internal sectors of the central-southern Apennines were marginally involved in crustal thinning that affected the southern Tyrrhenian, with the formation of NE–SW listric faults bordered by NW–SE oriented strike-slip faults (Casciello et al. 2006). While the combined activity of these tectonic structures led to the identification of large Tyrrhenian coastal depressions and probably promoted the genesis of most of the intermontane basins located in the internal and axial sectors of the central-southern Apennines, the external portions of the chain remained under the control of thrust tectonics.

During the Middle Pleistocene, the flexural retreat of the Adriatic plate and tectonic shortening suddenly stopped (Patacca & Scandone 2001; Ascione et al. 2012). Furthermore, around 0.7 My the complete detachment of the subducting slab occurred (Wortel & Spakman 2000). This is reflected in a general uplift of the whole chain (Cinque et al. 1993; Hippolyte et al. 1994) and the onset of extensional tectonics, characterized by a NE-SW sense of extension (Cinque et al. 1993; Hippolyte et al. 1994; Montone et al. 1999) that controlled the landscape response in this chain sector.

Data useful for the long-term morphoevolutive model

Hereafter, the main geological and geomorphological data available for the three study sectors are presented, highlighting the chronological and morpho-stratigraphic markers used to support the identification of the main stages of the long-term evolution of the Molise Apennines.

The SW Sector

The current orography and hydrography of this sector is the result of its complex tectonic-stratigraphic setting, characterized by alternating structural highs (mountain areas) and lows (alluvial plains and intermontane basins), generally bounded and intersected by faults, some of which are still active (Amato et al. 2014).

The most ancient landscape features are located in the high mountain areas and represented by gentle erosional landscapes mainly generated by fluvial and karst processes (Aucelli et al. 2013). These erosion surfaces are of varied extent and located between 1300 and 1800 m a.s.l. in the Matese Mountains and between 1000 and 1400 m a.s.l. in the Montagnola di Frosolone massif, but variously displaced by tectonics and difficult to group into separate orders.

Although no chronological constraints are available for these oldest landscape markers, their genesis can probably be referred to the first phases of morphogenesis that occurred immediately after the emersion of this sector. Published data on the beginning of the morphogenesis of the central-southern Apennines (Bosi et al. 1996; Ascione et al. 1997, 2012, 2014; Ascione & Cinque 1999; Basili et al. 1999; D'Alessandro et al. 2003; Schiattarella et al. 2006, 2008; Giano & Schiattarella 2014; Gioia et al. 2014; Miccadei et al. 2014) suggest that its internal portion gradually emerged during the Pliocene. Particularly, these authors have demonstrated that the emersion and, therefore, the beginning of the morphogenesis occurred gradually from the NW (Abruzzo-Molise sector) to SE (Campania-Lucania sector), between the Early–Middle Pliocene and the Lower Pleistocene. This thesis is also supported by the lack of Pliocene deposits throughout the internal sector between the Matese, Montagnola di Frosolone and Venafro mountains as well as within the surrounding intermontane basins.

The remnants of palaeosurfaces recognized at lower heights and the Quaternary infills of the major morphostructural depressions are the most suitable for the reconstruction of the long-term evolution of the SW Sector. Both the Montagnola di Frosolone Mountain and the northern slope of the Matese Massif are rich in such palaeosurface remnants (Fig. 2) that are the response, as discussed below, to the successions of tectonic events that occurred in this sector of the chain.

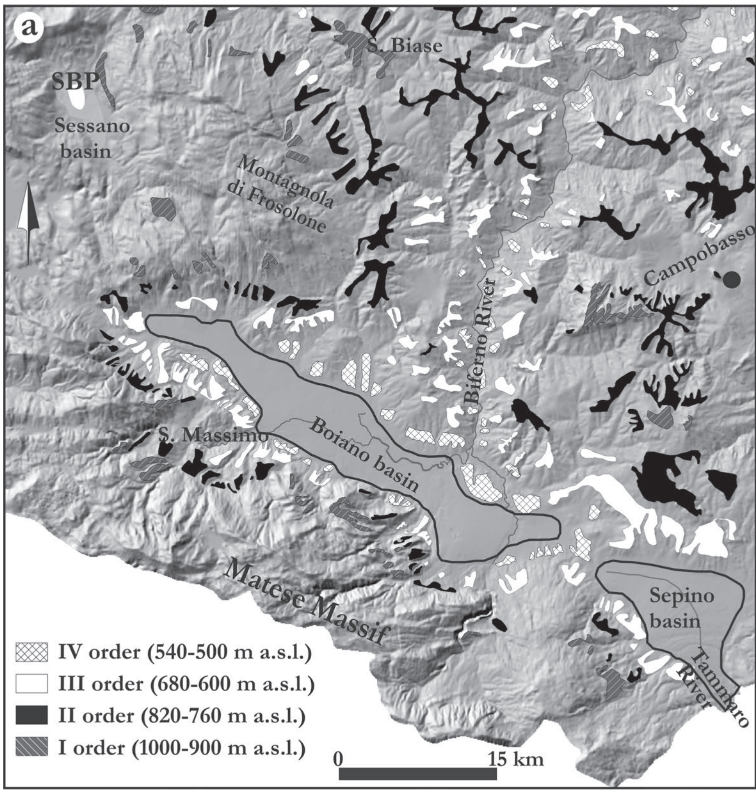
Uplift phases and consequent valley downcutting alternated with phases of substantial stability of local base levels of erosion during which fluvial denudational processes prevailed (valley flank retreat and valley floor widening). Most of the palaeosurfaces are of erosional origin, cut into the Mesozoic–Cenozoic bedrock, and only in some cases thin covers of Quaternary deposits are present. Taking into account their distribution and height above sea level, these palaeosurfaces were referred to four distinct orders (Fig. 2): I order (1000–900 m), II order (820–760 m), III order (680–600 m) and IV order (540–500 m).

The I order palaeosurface is generally cut into the bedrock and appears reduced to small and elongated ridges, hanging ca. 500 m over the Boiano basin floor. Although no chronological constraints are available for this order, regional geological-structural and geomorphological data allow us to tentatively refer its genesis to the Lower Pleistocene. In fact, close to Campobasso (Fig. 2), this order is cut into the Pliocene fluvial-transitional succession of the Campobasso (Vezzani et al. 2004) and M. Vairano Conglomerates (Pappone et al. 2010) that suggest a post-quem term for its development (Fig. 2b).

The II order palaeosurface, generally of erosional origin, is locally cut into the fluvial-lacustrine deposits that crop out at Serra S. Giorgio near S. Massimo and contain tephra layers that have been recently Ar/Ar dated to 649±21 and 621±6 ky BP (Di Bucci et al. 2005). This data allows us to refer the genesis of the II order palaeosurface to the Middle Pleistocene (Fig. 2b), and more precisely to ca. 600 ky BP.

The III order palaeosurface is mainly constituted by erosional and/or depositional planar surfaces that are found both along the borders of the Sepino, Boiano and Isernia intermontane basins and the flanks of major valleys (Aucelli et al. 2011, 2014). This III order can also be dated to the Middle Pleistocene, to after 400 ky BP. In fact, some remnants of this order are cut into fluvial-palustrine deposits cropping out in the Sessano intermontane basin (SBP, Fig. 2a) that contain a tephra layer dated by Ar/Ar to 437 ky BP (Russo Ermolli et al. 2010; Amato et al. 2011).

Finally, the IV order palaeosurface, represented by both erosional and depositional surfaces, is found along the borders of the intermontane basins and the major valley flanks at a few tens of metres above the local base levels. The presence of the Neapolitan Yellow Tuff (15.3 ky BP, Deino et al. 2004) within the fluvial-marshy succession of the Boiano basin infilling, allows us to hypothesize for this order a late Upper Pleistocene age.



b

Order	Matese	Montagnola	Δh	AGE
IV	540-520 m a.s.l.	520-500 m a.s.l.	40-20 m	Upper Pleistocene
III	680-620	640-600	200-120	<400 ky BP
II	820-800	800-760	340-280	<600 ky BP
I	1000-960	980-900	520-420	Lower Pleistocene

Fig. 2. a — Distribution of the four orders of recognized palaeosurfaces in the SW sector (from Amato et al. 2014, modified); **b** — table summary reporting the height a.s.l. of the palaeosurface remnants along the NE slope of the Matese Massif and along the S slope of Montagnola di Frosolone, their height above the Boiano basin floor (Δh in m) and their age attribution.

The major structural depressions located in the SW Sector are grabens or semi-grabens and bordered by generally NW–SE, NE–SW and E–W oriented high angle faults. Their basin floors are characterized by a quite flat morphology due to aggradation and are only partly incised by rivers. Infill successions reach thicknesses of 80 to 240 m (Isernia 80 m, Sessano >80 m, Venafro >200 m and Boiano 240 m) and are mainly made of fluvial-marshy and lacustrine deposits with intercalations of volcaniclastic layers and palaeosols (Amato et al. 2014). Based on stratigraphic features, several phases of deposition, favoured by tectonic subsidence, are distinguished.

Collected chronostratigraphic data highlight that the infill successions directly overly the Miocene and/or Mesozoic bedrocks and are made of Lower Pleistocene lacustrine-palustrine and fluvial marshy deposits and Middle Pleistocene and Upper Pleistocene–Holocene fluvial marshy and alluvial fan deposits (Russo Ermolli et al. 2010; Aucelli et al. 2001, Amato et al. 2012, 2013, 2014).

The genesis and early stages of evolution of these basins occurred under the control of tectonic transtension, while their further evolution was guided by extension (Fig. 3) that replaced the transtensive regime at the beginning of the Middle Pleistocene. The subsequent intensification of the extensional regime, acting along generally NW–SE oriented high angle faults, caused an increase of subsidence within the basins that favoured the sedimentation of thick fluvial-marshy successions rich in tephra layers and reworked volcaniclastic material (Amato et al. 2014), and also caused the terracing of some portions of the infill successions (Amato et al. 2011, 2014) (Fig. 3). The intensity of tectonic processes seems to be very high from 0.6 to 0.4 My BP, then gradually decreased starting from the upper part of the Middle Pleistocene (Amato et al. 2014). Furthermore, during the late Middle Pleistocene and the Upper Pleistocene–Holocene, sedimentation was also controlled by more intense 100 ky cycles climatic fluctuations.

The Central Sector

The Central Sector is characterized by a hilly morphology and elevations ranging between 150 m (minimum elevation of the main valley floors) and 1000 m (maximum height of some isolated peaks). The prevalence of mostly pelitic rocks (Molise and Sannio basin units) with scarce to nil permeability has allowed the development of a dense fluvial network. By flowing to the Adriatic Sea across the thrust-belt system, the main rivers (Trigno and Biferno) have incised deep valleys in which ancient fluvial and slope deposits are practically lacking, highlighting that river downcutting and valley widening have largely prevailed over sedimentation. Therefore, in this sector, the long-term landscape evolution is essentially indicated by erosional landforms, as highlighted by Aucelli et al. (2012)

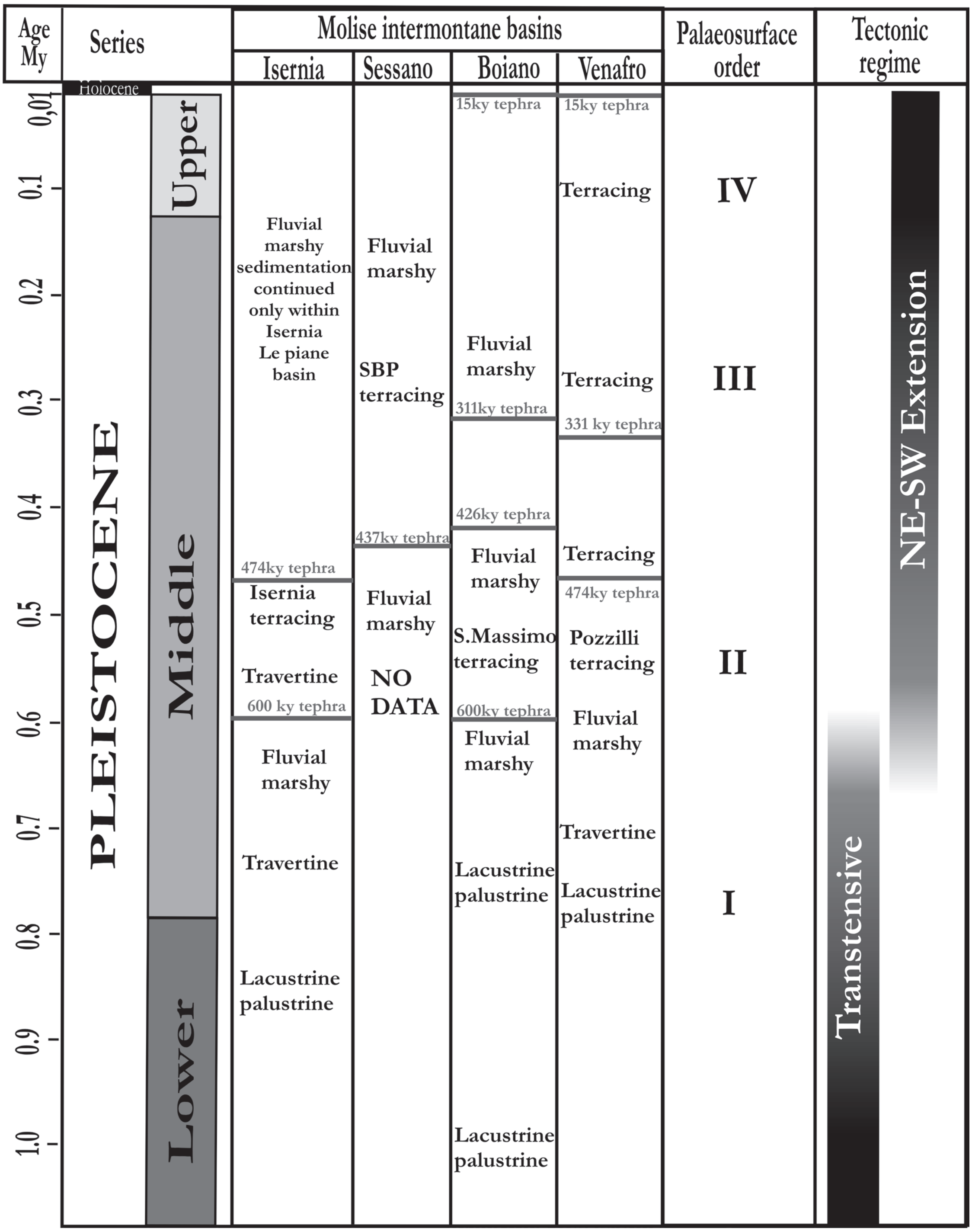


Fig. 3. Synthesis of major geomorphological and depositional events and related palaeo-environments reconstructed within and around the Molise intermontane basins during the Pleistocene, and reconstructed tectonic regimes (data source: Russo Ermolli et al. 2010; Amato et al. 2011, 2012, 2014; Aucelli et al. 2011, 2012).

and, specifically, by relics of ancient erosion surfaces and hanging valley side glacis. The first ones coincide with narrow water divides located at various heights, while the valley side glacis are found along the valley flanks of the main rivers and tributaries. Precisely, these glacis coincide with the downslope terminations of gentle convex-concave hillslopes, typically represented by almost planar surfaces dipping very gently toward the valley axes, and separated from the thalwegs by steep high fluvial scarps.

Four orders of palaeosurfaces could be distinguished in this sector (Fig. 4): I order (980–900 m), II order (800–760 m), III order (640–600 m) and IV order (540–500 m).

The remnants of the I order palaeosurface are generally cut into the bedrock and appear reduced to small and elongated

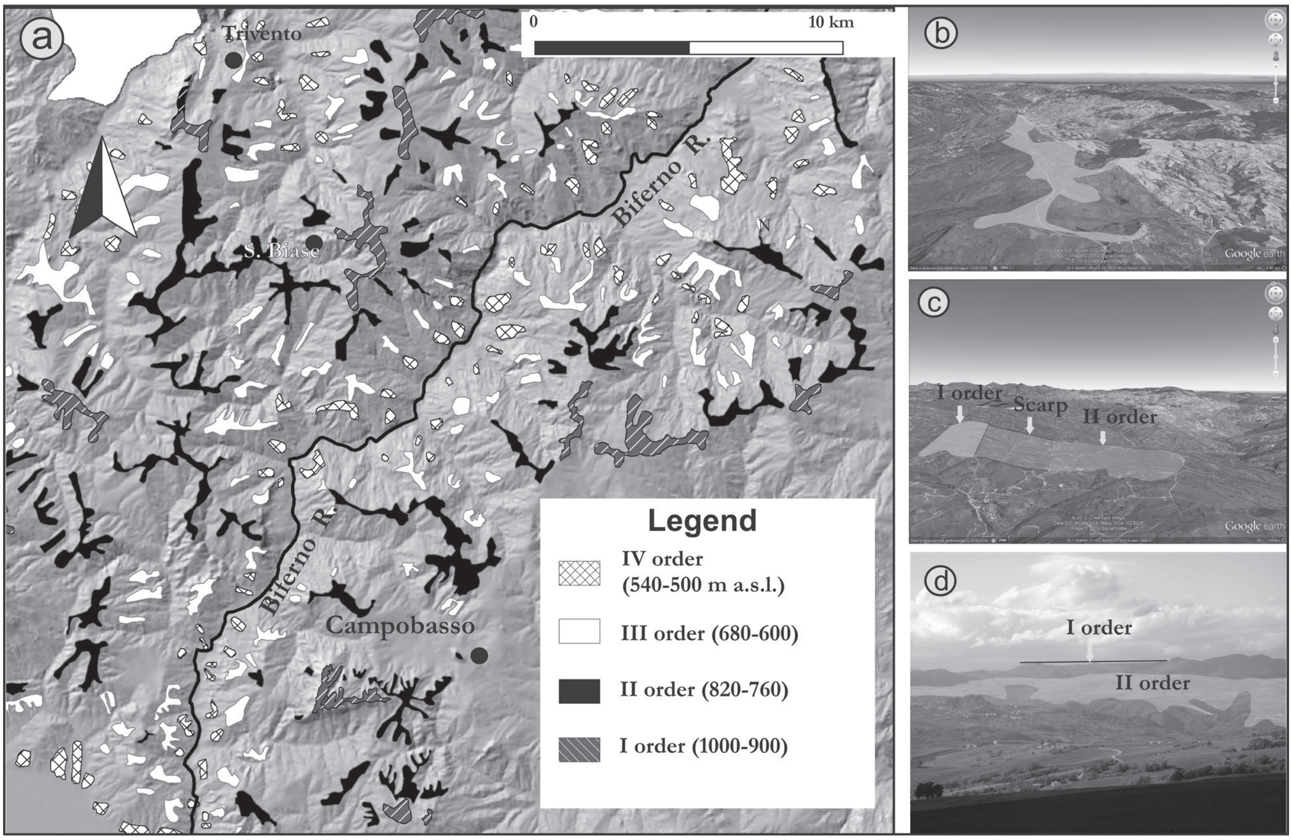


Fig. 4. a — Sketch map showing the distribution of the four orders of palaeosurfaces recognized in the Central Sector of the Molise Apennine; **b** — a large relict of the I order palaeosurface forming the top of the local relief in the Trivento area; **c** and **d** — examples of major I and II order palaeosurface remnants.

ridges. Although no chronological data are available for this order, some morpho-stratigraphical data allow us to hypothesize an Early Pleistocene age. In fact, along the NE slopes of Montagnola di Frosolone, the I order is clearly younger with respect to the oldest surfaces of the high-mountain area between 1400–1000 m a.s.l. that, as mentioned above, are tentatively referred to the Pliocene. Furthermore, in the medium reaches of the Trigno and Biferno river valleys, the I order remnants coincide with flat to rounded summit areas including the major water divides, and close to Campobasso cut the Pliocene transitional and fluvial deposits of the Campobasso Conglomerates (Vezzani et al. 2004) and M. Vairano Conglomerates (Pappone et al. 2010). These data, given the lack in this sector of Middle to Upper Pliocene deposits (Casnedi et al. 1981), most likely can be proposed as post-quem terms in order to tentatively date the I order palaeosurface, allowing us to suggest that this sector was already substantially emerged during the Pliocene.

The II order palaeosurface is represented by remnants both in summit position and hanging along valley sides, forming respectively narrow water divides and erosional valley side glacis (Fig. 4). This order is correlated to the II order palaeosurface recognized in the SW Sector, in the areas around the Boiano basin that belong to the Adriatic flank of the chain, and constrained to the first part of the Middle Pleistocene (Aucelli et al. 2011; Amato et al. 2011, 2014).

Starting from the Middle Pleistocene, the general uplift of the Apennine chain enhanced fluvial downcutting, which was also favoured by climatic changes. Valley evolution occurred through several phases of river incision alternating with phases of substantial nil incision during which valley flank retreat and decline due to lateral erosion and slope processes dominated (Aucelli et al. 2001, 2010, 2012). Consequently, in this sector, only some relics of valley side glacis and terraced surfaces are found, hanging some tens of metres above the present valley floors and forming remnants of the III and IV order palaeosurface. Taking into account their present heights above the valley floors and the supposed former valley gradients they can be tentatively correlated to the III (680–600 m a.s.l.) and IV (540–500 m a.s.l.) orders of the well-dated palaeosurfaces present in the SW Sector and, therefore, constrained between the Middle and Upper Pleistocene. In particular, the III order palaeosurface can be constrained to the late Middle Pleistocene on the basis of the age of the SBP palaeosurface of the very close Sessano Basin (Aucelli et al. 2011; Amato et al. 2011, 2014) dated to ca. 0.3 My BP. The spatial distribution, aspects and gradients of the III and IV order palaeosurfaces indicate that the valley axes of the Trigno, Biferno and Fortore rivers had already reached their current position in the Middle Pleistocene. During the Late Pleistocene, alternating phases of aggradation and river incision have allowed the development of some alluvial terraces, now hanging only a few metres above the current valley floors (Rosskopf & Scorpio 2013; Sgrosso & Naso 2011).

The NE Sector

The NE Sector extends from the Frentani Mountains (about 40 km from the coast) to the Adriatic Sea (Fig. 5). The internal portion of this sector corresponds to the outer wedge of the chain where the Molise basin units crop out. It mainly lies at 400 to 600 m a.s.l., although some peaks located near its inner margin reach altitudes of up to 900–1000 m. The external portion of this sector reaches a maximum elevation of ca. 350 m a.s.l. and corresponds to the foreland area (wedge-top basin) dominated by the Plio–Pleistocene regressive sedimentary succession (Amorosi et al. 2009).

Within the internal portion, the landscape is dominated by elongated NW–SE oriented ridges alternating with secondary river incisions orientated parallel to the tectonic structures of the chain. Ridges and valley incisions coincide with anticlinal and synclinal fold structures that are underlain respectively by calcareous lithologies and clayey terrains. The external portion, instead, is characterized by terraced planar surfaces dissected by fluvial incision that appear wider and better preserved when underlain by arenaceous and conglomeratic lithologies.

During the Middle Pliocene–Early Pleistocene time interval, the internal portion of the NE Sector was affected by thrust tectonics that determined the growth both of the outer wedge and the mountain front, while the external portion was still under marine domain. In the late Early Pleistocene, tectonic activity caused a further NE shift of the coastline and the deposition of nearshore deposits in the external portion. The transition from Early to Middle Pleistocene is marked by the last phase of tectonic activity that also involved the Apennine frontal thrust, with the ensuing emersion of the entire NE sector and the instauration of alluvial environments. The following regional uplift caused river downcutting and promoted the development of the terraced palaeolandscapes.

Four orders of palaeosurfaces have been distinguished (Fig. 5a) at altitudes between 10 and 625 m a.s.l. The I order palaeosurface is a summit erosion surface located at altitudes ranging from 550 to 625 m and represents the oldest landscape recognized in this sector (Fig. 5b). Its remnants are largely concentrated in the internal portion and of limited extension, with the only exception of the remnant present in the S. Croce di Magliano area (Fig. 5a). The genesis of this palaeosurface is related to the reshaping of the mountain front during the Early Pleistocene and, therefore, is tentatively correlated to the formation of the I order palaeosurface in the Central Sector.

The II order palaeosurface (PS1 in Bracone et al. 2012a), is located between 225 and 500 m a.s.l. It is cut into the Qc1 sequence, the first sedimentary cycle of the Campomarino Conglomerates (early Middle Pleistocene, Bracone et al. 2012a), and, therefore, can be attributed to the early Middle Pleistocene.

The III order palaeosurface (PS2 in Bracone et al. 2012a) is of depositional origin and found in the external portion of the NE Sector at altitudes ranging from 75 to 215 m a.s.l. (Fig. 5a and c). Its remnants are characterized by a N-NE dip and are larger when compared to the I and II order palaeosurface remnants (Fig. 5a). This palaeosurface coincides with the top of the palaeosol that closes up the Qc2 sequence, the second sedimentary cycle of the Campomarino Conglomerates (Bracone et al. 2012a), and, therefore, is Middle Pleistocene in age. A palaeosol, correlated to the previous one, is present immediately north of the Molise area, in the Abruzzo and Marche foothills, and dated to MIS 9 (Di Celma et al. 2015), confirming the Middle Pleistocene age of the III order palaeosurface.

During the second part of the Middle Pleistocene, a generalized regional uplift deactivated the III order palaeosurface and caused the entrenchment of the river network.

Tectonic uplift along with glacio-eustatic sea level fluctuations deeply controlled processes of valley downcutting and led to the formation of river terraces and the IV order palaeosurface (PS3 in Bracone et al. 2012a) which is located at elevations of 10 to 60 m a.s.l. Generally, this palaeosurface is cut into Plio–Pleistocene units, but locally (at 10 m a.s.l.) has a depositional origin associated with Upper Quaternary nearshore or transitional deposits. Although no absolute data are available, the developed chronostratigraphic framework (Bracone et al. 2012a; Amorosi et al. 2016) allows us to constrain the age of this palaeosurface to the Middle–Late Pleistocene.

As remarked by Amorosi et al. (2016), from 200–150 ky BP the main river valleys formed and the glacio-eustatic fluctuations mainly produced their effects in the coastal plains of the study area. Particularly, in the Biferno valley alternating glacial and interglacial conditions produced a multiple buried palaeovalley system formed by alternating phases of valley incision and filling, as testified by buried river terraces and a valley infill made up of alluvial, transitional and nearshore deposits of Late Pleistocene to Holocene age (Amorosi et al. 2016). Especially, transgressive and highstand deposits in the coastal plain showed a clear transition from alluvial to transitional and marine environments (D'Amico et al. 2013; Amorosi et al. 2016) during the Holocene transgression.

The long-term landscape evolution of Molise region

Below we discuss the main stages of the tectonic and landscape evolution that are reconstructed for the Molise sector of the central-southern Apennines and schematically illustrated in Figure 6.

The starting point of our reconstruction is the tectono-stratigraphic setting acquired by the Molise Apennines due to tectonic compression during Upper Miocene. The latter, in fact, caused a strong shortening of the accretionary prism. During

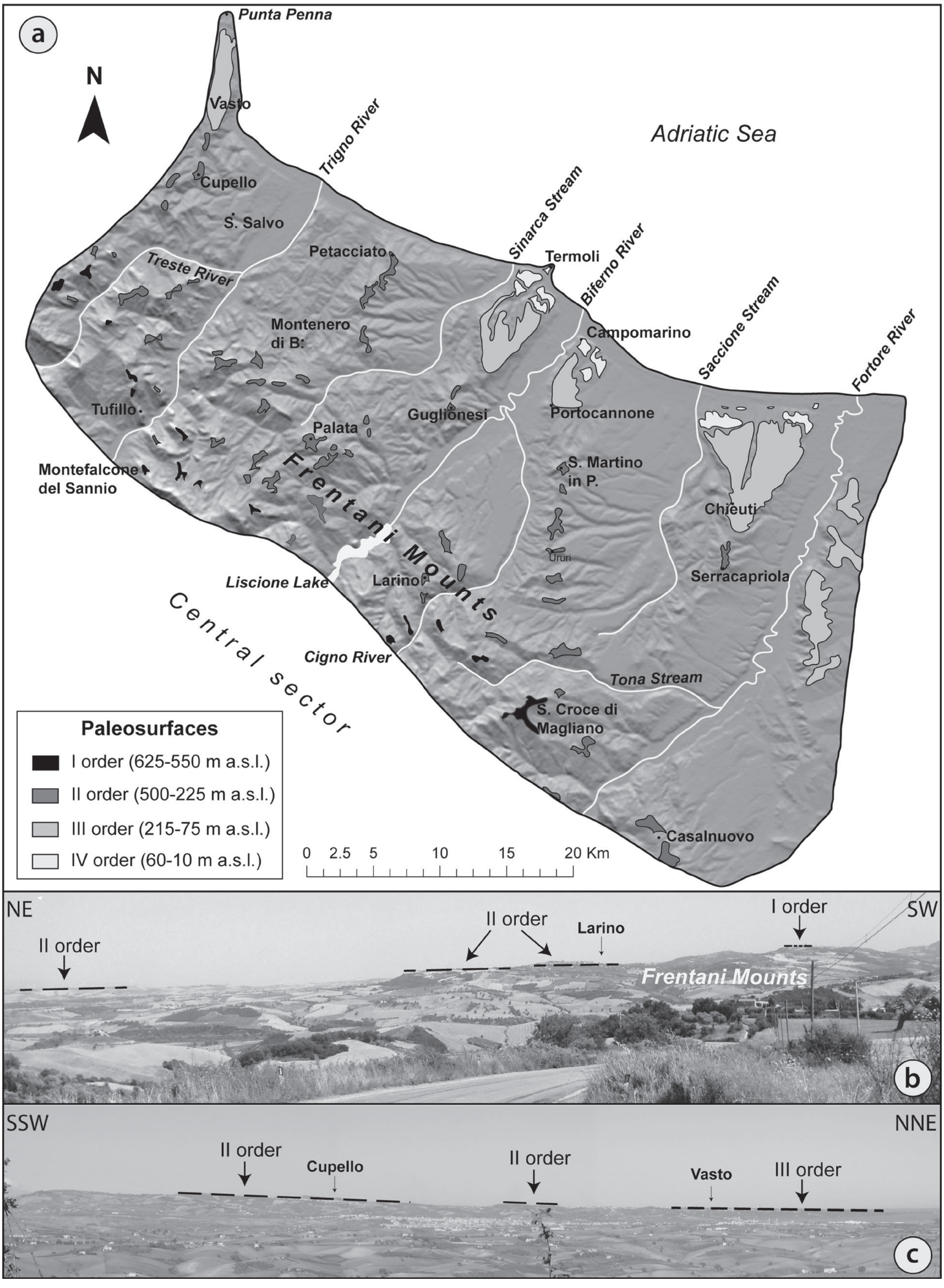


Fig. 5. a — Sketch map showing the distribution of the four orders of paleosurfaces recognized in the NE sector of the Molise Apennine; **b** — panoramic view of the I and II order paleosurfaces; **c** — panoramic view of the II and III order paleosurfaces present on the left of the Trigno valley. Please note that the differences in height between the II and III order paleosurfaces are not significant due to the elevated distance of the observation point.

this phase of shortening, the prism incorporated the sedimentary covers referring to the Mesozoic–Cenozoic palaeogeographic carbonate platform and basin domains located on top of the subducting Adriatic plate. Especially the Matese-Frosolone carbonate platform and the Molise basin units were incorporated as testified by the Upper Tortonian–Lower Messinian foredeep deposits (Molise Flysch, Pappone et al. 2010) placed on top of them.

During the Early Pliocene (Fig. 6a) compressive tectonics led to a complete emersion of the internal sector of the chain (our SW Sector), while the Pliocene sea still occupied the remaining part of the Molise Apennines with wedge-top basins (Tona Formation) placed in the frontal zones of the accretionary prism and connected eastwards to the foredeep domain.

In the Middle–Late Pliocene (Fig. 6b), the migration of the thrust sheets toward the Adriatic foreland induced the deformation of the buried Apulian units through the development of duplex structures that caused the thickening of the accretionary prism. These processes produced the uplift of the chain and the consequent dismantling of the Sannio Units present on the roof of the accretionary wedge. These stages of structuring of the chain determined in the SW Sector the exhumation of the carbonate successions of the Matese-Frosolone units (Pappone et al. 2010; Cesarano et al. 2011), and in the Central Sector the enucleation of the S. Biase structural high (Mazzoli et al. 2000) which most likely represented the seaward limit of the Campobasso Conglomerates sedimentation.

The described configuration of the chain and the almost complete lack of Pliocene deposits above the thrust sheets in the internal sector leads us to presume that in this period most of the SW and Central sectors of the chain had already emerged. Conversely, the internal portion of the NE Sector was still occupied by wedge-top basins and the external portion by a foredeep basin.

Starting from the Late Pliocene–Early Pleistocene, the Sannio nappe on the Matese Massif and Montagnola di Frosolone Mountain was almost completely eroded, leaving an erosional landscape, remnants of which constitute the palaeosurfaces over 1000 m a.s.l.

During the Early Pleistocene (Fig. 6c), due to the onset of transtensive tectonics, a more complex landscape with structural highs and lows started to develop in the SW Sector. In the external portion of the NE Sector, instead, a marine wedge-top basin and the sedimentation of the Montesecco Clays persisted.

Particularly, starting from the late Early Pleistocene, the Molise intermontane basins, poorly drained, started to be filled with predominantly lacustrine and palustrine deposits. In the SW and Central sectors and in the internal portion of the NE Sector, now completely emerged, the I order palaeosurface started to be shaped. The intermontane basins were still subject to strong subsidence and continued to accommodate predominantly palustrine and fluvial-marshy deposits. Meanwhile, in the internal portion of the NE Sector compression continued to affect the frontal thrusts of the chain, enhancing the uplift and tilting of the Montesecco Clays and the formation of erosion surfaces, while the upper to lower shoreface Serracapriola Sands deposited in the external portion.

During the Middle Pleistocene (Fig. 6d), starting from ca. 700 ky BP, a NE–SW extensional regime became established that deeply controlled the further evolution of structural highs and lows in the SW Sector. This regime was characterized by at least two important paroxysmal episodes about 600 ky and 400 ky BP that preceded respectively the genesis of the II and III order palaeosurfaces. Within the intermontane basins, sedimentation gradually became predominantly fluvial-marshy thanks to the reduction of subsidence rates and the significant contributions of volcaniclastic deposits produced by several eruptions of the Roccamonfina volcano. Furthermore, regressive erosion caused the capture of the intermontane basins. As demonstrated by Amato et al. (2014), the capture of the Boiano basin occurred between 600 and 400 ky. In the Central Sector, major geomorphic events are related to the genesis of the II and III order palaeosurfaces during periods of relatively low uplift, although within an overall context of general uplift and consequent valley downcutting. In the NE Sector, the compression at the front of the accretionary prism promoted the sedimentation of the first cycle of the Campomarino Conglomerates, the Qc1 sequence, cut by the II order palaeosurface during the early Middle Pleistocene. After the deposition of the second cycle of the Campomarino conglomerates (Qc2), during a period of substantial tectonic stability, the III order palaeosurface developed. During the second part of the Middle Pleistocene, a generalized regional uplift caused the entrenchment of the river network and the consequent deactivation of the III order palaeosurface.

At the beginning of the last considered stage (Late Pleistocene–Holocene, Fig. 6e), the Molise sector of the Apennine chain had already reached its present setting. Regarding the SW Sector, among the most significant events are the reduction of subsidence rates in the intermontane basins and the genesis of the IV order palaeosurface. Meanwhile, in the Central Sector the deepening of river valleys and the intensification of landslide phenomena along the valley flanks continued, also favoured by first land cover changes due to human activities during the Holocene (Rosskopf & Scorpio 2013). In the external portion of the NE Sector, glacio-eustatic sea level changes caused repeated changes of the coastline position and consequent shifts from continental to littoral environments as well as the remodelling of the sea cliffs in the areas of Termoli and Campomarino.

Conclusions

The proposed reconstruction of the long-term landscape evolution of the Molise sector of the central-southern Apennines is based on the revision of already published data, integrated by some recent data collected by the authors, or not published or still under examination. The total of available data allowed us to propose, for the first time, a conceptual model of the palaeolandscape setting during the Early

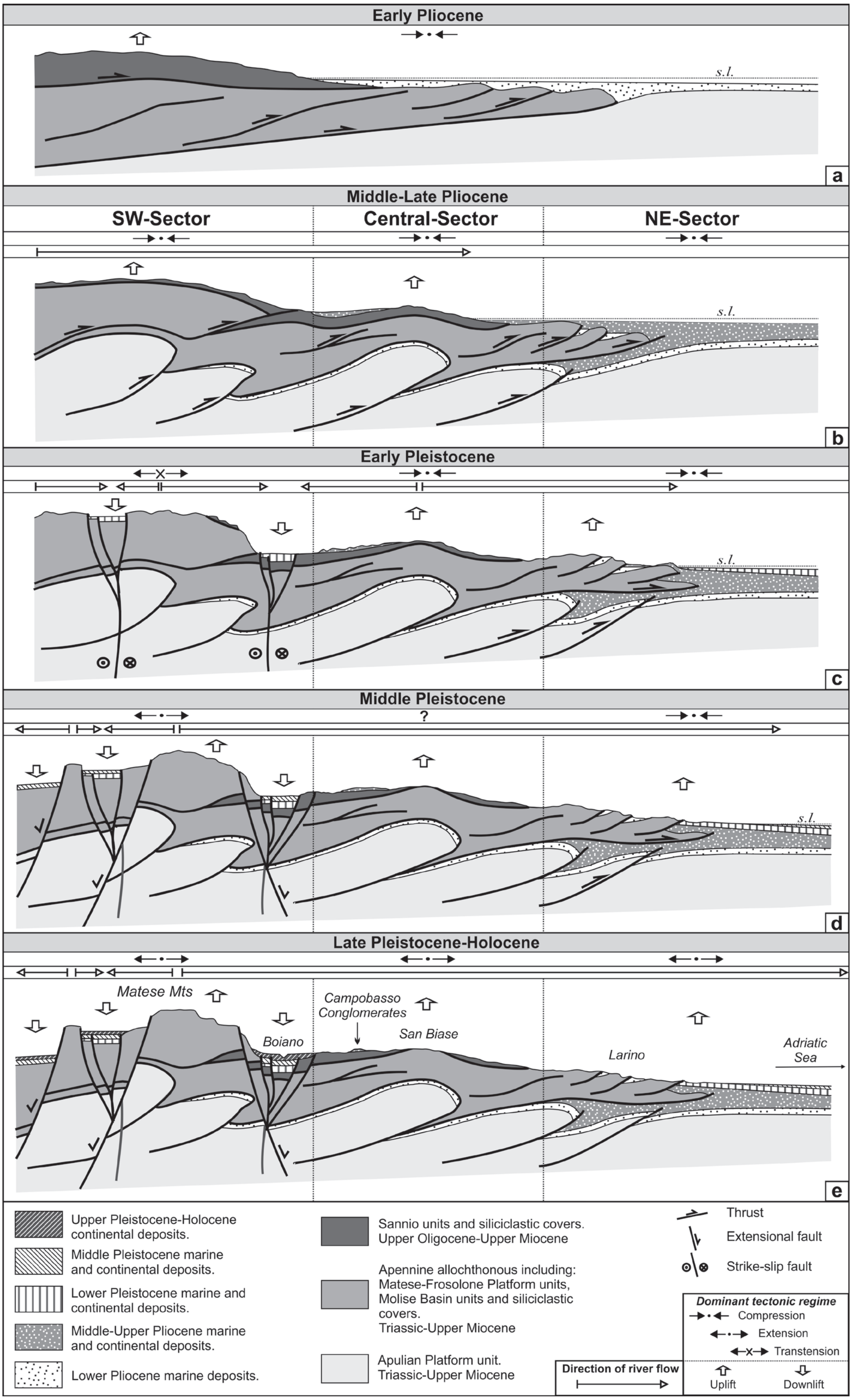


Fig. 6. Schematic geological cross sections across the Molise Apennine to the Adriatic coast (not drawn to scale) illustrating the overall stratigraphic-tectonic setting along with tectonic events and tectonics regimes that have characterized its SW, Central and NE sectors during various time intervals (**a**–**e**) starting from the Early Pliocene.

Pliocene and a reliable synthesis of the landscape evolution of the Molise Apennines since the Late Pliocene.

The main morpho-evolutionary stages that have occurred since the Late Pliocene mainly under the control of tectonic activity have been traced. The principal markers used are the chrono-stratigraphical records derived from infill successions of intermontane basins and Plio–Quaternary piggyback and foredeep successions, as well as the remnants of palaeosurfaces attributed to four orders at the regional scale and chronologically constrained between the Early and Late Pleistocene. These markers testify to the alternation of phases of substantial tectonic stability and uplift, allowing to assess their spatial-temporal distribution along the investigated transect, and highlighting that the emersion of the chain did not occur synchronously, but gradually from SW to NE. Especially, the internal SW Sector was already emerged in the Pliocene, while the NE Sector remained largely under the marine domain until the end of the deposition of the Montesecco Clays (Lower Pleistocene). Starting from the Middle Pleistocene, the evolution of the Molise area significantly differed from sector to sector. While the SW Sector was under the influence of NE–SW oriented extensional tectonics that promoted the further reshaping and widening of the morpho-structural depressions and their infilling, the Central and the NE sectors were mainly influenced by general uplift that controlled several cycles of valley floor incision and widening.

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