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Small catchments evolution on clayey hilly landscapes in Central Apennines and northern Sicily (Italy) since the Late Pleistocene

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ABSTRACT

The study aims to define a possible evolutionary geomorphological model of small catchments (i.e., <40 km^2) that characterise the clayey hilly landscape of Central Apennines and Northern Sicily piedmont for the late Pleistocene–Holocene (i.e., the last 20,000 years, from the last glacial stage to the Holocene climate amelioration). The study is based on an integrated approach incorporating (i) geomorphological surveys and mapping, (ii) dating of Quaternary continental deposits, and (iii) topographical and morphometrical processing. It combines the data collected from previous published investigations as well as new data, specifically related to the availability of geo-chronological markers, and helps outline a common evolutionary model. The selected small catchments are tributaries of major rivers in inland areas (small catchments of the inland hills of Tuscany, Marche, and Sicily) or flow directly to the coast (coastal small catchments in Abruzzo). For each area, the geomorphological features (clay dominated bedrock, erosional landforms and fluvial terraces, and erosional/depositional strath terraces) and the dating of Quaternary deposits (from <50kyr to 15kyr) were compared, reconstructing the morphometry of the probable late Pleistocene landscape configuration. The analysis of the results showed that, although currently characterised by different climatic and geo-structural conditions, the different basins underwent a common geomorphological evolution mostly since the late Pleistocene. During the last glacial stage, under cold climate rhexistasy conditions, the small catchments were dominated by low gradient erosional surfaces with the deposition of fluvial, colluvial, or slope deposits, resulting in the formation of uniform slopes and wide minor valleys. The Holocene climate warming, together with marine transgression and tectonic uplift, induced the incision and dissection of the erosional surfaces and the continental deposits via gravitational movements and rapid erosion processes up until the present-day landscape configuration. The control factors of this evolution are most likely linked to the climate changes at the beginning of the Holocene and the interplay with the changes in the local base level of the small catchments since the late Pleistocene, combining late Quaternary tectonic uplift, sea-level rise, and river/coastal incision.

1. Introduction

Rivers, from large ones to small streams, are among the primary agents of landscape development (Tucker, 2015). Several factors control the setting and development of rivers. Climate (Preece and Bridgland, 1999; Brocard et al., 2003; Whittaker, 2012), sea-level changes (Holbrook et al., 2006; Parlagreco et al., 2011), lithology and tectonics (Schumm et al., 2000; Di Biase et al., 2012; Piacentini and Miccadei, 2014; Stokes et al., 2017; Mather and Stokes, 2018), slope morphology (Pelletier, 2003; Castelltort et al., 2009; Perron and Fagherazzi, 2012; Cappadonia et al., 2016; Piacentini et al., 2018), and river terraces and alluvial fan dynamic interaction (Mather et al., 2017) are among the most important factors. In tectonically active areas, the combined effects of climate and tectonics can lead to cyclic changes in river dynamics ranging from valley incision to widening and aggradation and eventually to the creation of fluvial terraces as rivers return to incision (Wegmann and Pazzaglia, 2009). Tectonic activity and sea-level changes are interrelated, and their system effects can either be positive or negative, either amplifying or suppressing the river response in terms of erosion/incision and sedimentation/aggradation. The balance of sediments necessary for the creation of strath surfaces and fill terraces depends on the amount of sediment supply in the entire hillslope-valley system linked to climatic changes (Bridgland and Westaway, 2008; Wegmann and Pazzaglia, 2009). In particular, in cold dry periods, when the vegetation cover is scarce or absent, large amounts of loose sediments are available on the hillslopes that can be carried along with the water flow, leading to an increase in the sediment

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supply of rivers. Conversely, in warm-humid periods, when the vegetation cover is greater, rivers receive a smaller sediment supply, and this induces a higher erosion capacity and incision in rivers and streams. On a small scale, rivers can carve some minor landforms along their course in response to local tectonic activity (e.g. river bends, knick points, and alluvial fans). The magnitude and the effectiveness of this response are influenced by basin rock type. Generally, hard rock type records river changes with topographical signatures and preserves landforms, while in case of soft rocks, the landforms produced can be readily disappear with the erosion of rocks (Stokes et al., 2017; Keen-Zebert et al., 2017).

Small catchments and low-order drainage systems, especially when set on clayey bedrock, respond more rapidly to the transformations of physical environment than large ones with regard to the rearrangement of their slope morphometry (Mizutani, 1996; Pelletier, 2003; Della Seta et al., 2007; McGuire and Pelletier, 2016; Brandolini et al., 2018; Harrison et al., 2019; and references therein). Moreover, the initial morphological and morphometrical conditions play a crucial role in driving the evolutionary response of small catchments, thus determining the geomorphological response in terms of sedimentation/incision dynamics (Dotterweich, 2008; Buccolini et al., 2010; Harrison et al., 2019; Pelletier, 2003; Buccolini and Coco, 2013; Tucker, 2015). For this reason, it is important to understand the mechanisms that regulate (and have regulated in the past) the evolution of small river systems. This, in turn, can lead to an improved understanding of the recent geomorphological dynamics that have led to the current landscape configuration, primarily through gravitational hillslope and fast soil erosion processes (i.e., badlands).

The present study aims to help understand the rapid late Pleistocene–Holocene (last 20,000 years) geomorphological evolution of hilly small catchments set on the side slopes of major valleys or along the present coastal slopes of the Central Apennines and Sicily hilly piedmont. This phase corresponds to the climate amelioration following the peak of the last cold stage (LGM, Last Glacial Maximum). Four case studies were considered in areas located in Tyrrhenian, Adriatic, and Northern Sicily hills for which extensive studies have been conducted over the last two decades (e.g., Abate et al., 1999; Ciccacci et al., 2003; Della Seta et al., 2007; Pascucci et al., 2007; Di Maggio et al., 2009; Buccolini et al., 2007, 2010, 2014; Miccadei et al., 2012, 2013, 2017; Martini et al., 2013; Cappadonia et al., 2016). These areas show homogeneous physiographic features and different morphostructural conditions and are considered to be broadly representative of the typical Central Apennine and Northern Sicily hilly piedmont landscape. They are characterised by two different morphostructural conditions:

A) inland catchment tributary of the main river valleys, located up to several tens of kilometres from the present coastline:
- Formone River in Tuscany for the Tyrrhenian hilly sector;
- Mount Ascensione in Marche for the Adriatic hilly sector;
- Imera Settentrionale River in Sicily for the Sicilian hilly sector.

B) coastal catchments, flowing directly to the coastline:
- Atri area in Abruzzo for the Adriatic coastal sector.

Some of the data used for this work were derived from previously published studies (for the Formone case study, see Buccolini et al., 2014; for Atri and Mt. Ascensione case studies, see Buccolini et al., 2010). These studies were reviewed to obtain a uniform and comparable dataset of small catchments on both sides of the Apennines chain and include geomorphological surveys, geo-chronological dating of Quaternary deposits, and morphometric analyses. Data from new investigations in the Imera Settentrionale case study were integrated with the previously existing data to extend the comparison from the hilly piedmont of the Central Apennine chain to Sicily. The new investigations and the revision and integration of existing ones were based on a detailed geomorphological survey for the characterisation of Quaternary continental deposits and erosional landforms and surfaces.

The study areas are characterised by analogous geological settings (clayey bedrock, i.e., very fine, cohesive, impermeable, and highly erodible sedimentary sequences dominated by clays of variable mineralogy, with low ratios of sand and silt, and thin sand levels), morphometry (i.e., <40 km2 catchments on hilly landscape from >1000 m to the sea-level), morphochronological features (Late Pleistocene-Holocene evolution), and geomorphological dynamics (water- and gravity-driven processes). However, they feature different climatic, morphostructural and geodynamical contexts (from extensional regions to transitional sectors, from compressional to extensional areas, Figs. 1 and 2). Nevertheless, they have undergone a similar geomorphological evolution in the last 20,000 years (during the climate amelioration since the LGM), with increased erosion amounts and incision rates that have defined their current physiographic and geomorphological configurations.

To pursue the main aim of this study, we revised and integrated the new and previous data to compare and correlate the local geomorphological evolution of small hilly clayey catchments within a regional framework. This analysis showed that although currently characterised by different climatic and geo-structural conditions, the catchments underwent a common recent geomorphological evolution (during late Pleistocene–Holocene). The possibility of a comparable and simultaneous evolution was explored, due to the changes in the erosion/sedimentation regime at the Pleistocene–Holocene transition. This suggested a simplified model summarizing the late Quaternary evolution of small catchments set on clayey slopes in the Central Apennines and Sicily hilly areas.

2. Geological and climatic setting

The landscape of peninsular Italy and Sicily is characterised by the Apennines chain, the related hilly piedmonts, and their insular prolongation. The Apennines chain was generated by the subduction of the Adriatic plate under the European plate towards the west; its back-arc basin was located to the west and corresponds to the Tyrrhenian sea (Fig. 2). The chain shows a typical thrust belt geometry NE verging, dissected by several younger normal faults, whereas the piedmont areas mainly feature extensional basins to the west and buried thrusts overlain by homocline plateau, mesa, and cuesta landscapes to the east. The Apennines from northwest Italy to Sicily form an asymmetric arc, which is relatively young and generated during the last 5–15 My, even though structures related to earlier subduction phases are present within the belt. The thrust sheets of the central-northern Apennines experienced a counterclockwise rotation, whereas a stronger clockwise rotation was observed in the shorter Sicilian thrust belt, which represents the southernmost Apennines sector; an overall extensional tectonic is presently prograding forward, just behind the compressive belt. Throughout the Apennines, the eastward migrating extension is coeval with compression in adjacent thrust-fold belts and ranges from the Tortonian, in the western part, to the Pliocene-Pleistocene, in the eastern part. Next, during the Pliocene–Pleistocene, the central portion of the Apennine underwent high subsidence rates because of the eastward rollback of the hinge of the west dipping Apennine subduction. The southern portion of the chain, after the Pliocene-Early Pleistocene subsidence, underwent a generalised uplift since the Middle Pleistocene (Doglioni and Flores, 1997; Patacca et al., 2008; Vezzani et al., 2010; Carminati and Doglioni, 2012; Faccenna et al., 2014).

More specifically, the typical hilly landscape from Central Italy to Sicily along the Apennines piedmont and coastal area, within which the four study areas were selected, consists of low gradient hills shaped on extensive marine clayey formations belonging to Miocene, Pliocene, and Pleistocene sedimentary cycles (Fig. 3). Along the Adriatic piedmont of the Apennines and in Northern Sicily, these formations mainly consist of marine clays and sands with interbedded gravels and conglomerates,

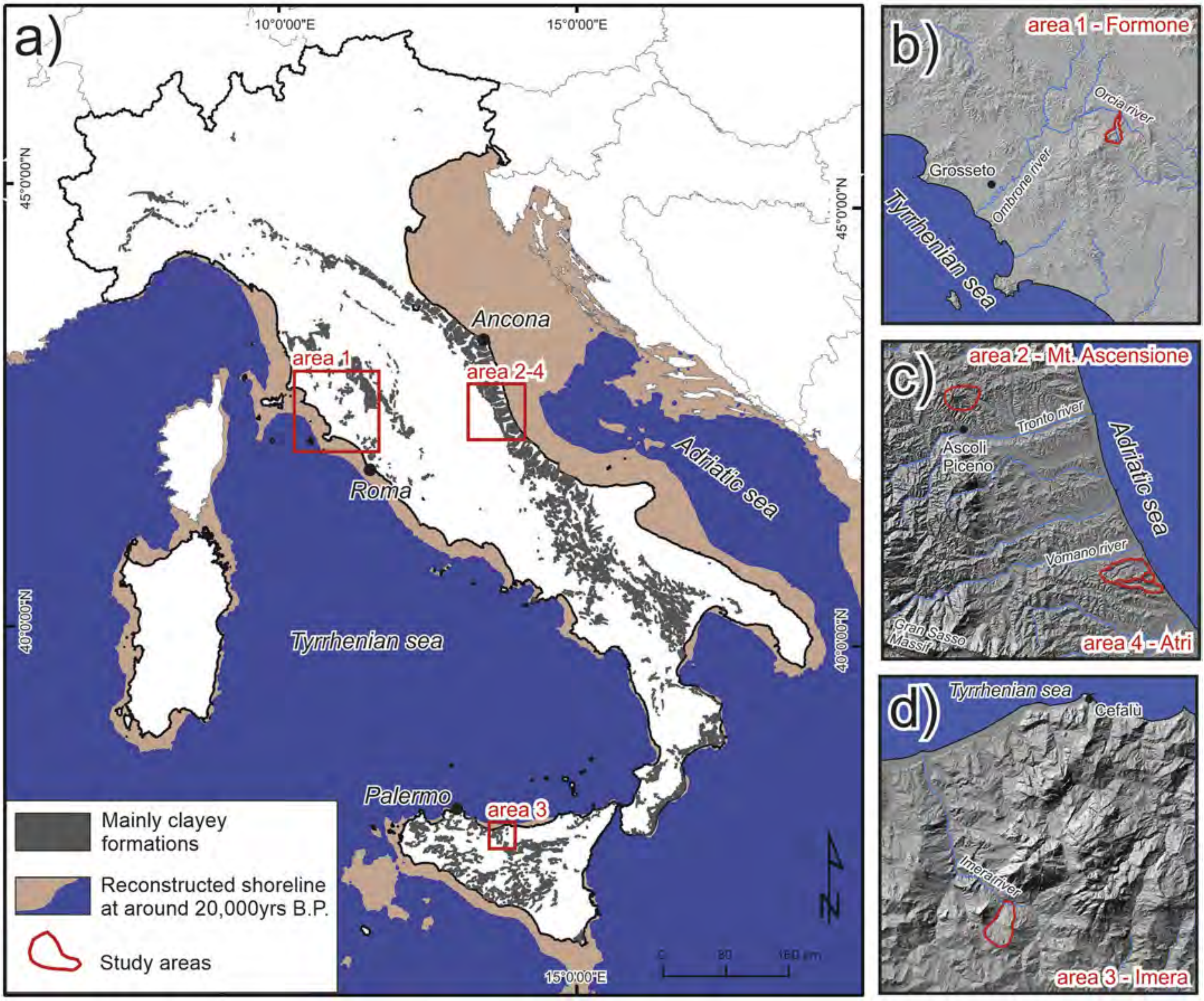


Fig. 1. a) Clayey hilly landscapes in Italy and reconstructed shoreline at ~20,000 yrs. B.P. (Last Glacial Maximum; modified from Lambeck et al., 2004); black boxes indicate the location of figure b, c, and d. b) location map of the Formone river area (Area 1); c) location map of the Mt. Ascensione (Area 2) and the Atri area (Area 4); d) location map of the Imera Settentrionale river area (Area 4).

arranged in roughly coarsening upward sequences. They belong to the Pleistocene foredeep successions deposited during the last stages of the Apennine chain formation and the emergence of the piedmont areas. They have been uplifted since the Early Pleistocene with rates ranging from 0.2 mm/yr along the coastal areas and 0.5–1.0 mm/yr along the chain front (D'Agostino et al., 2001; Centamore and Nisio, 2003; Pizzi, 2003; Cantalamessa and Di Celma, 2004; Cyr and Granger, 2008; Buccolini et al., 2010; Di Celma et al., 2015). Along the Adriatic and the Northern Sicily coast, the sedimentary cycle ends in the Middle Pleistocene with a thick sequence of sands, gravels, and conglomerates of fluvial–deltaic and coastal environments (Bigi et al., 1995; Cantalamessa and Di Celma, 2004). The present structural setting comprises regional homoclines, gently dipping towards NE in the Adriatic piedmont and towards the north in Northern Sicily. These structures have been cut by major dip-stream valleys since the Middle Pleistocene (D'Alessandro et al., 2003; Di Maggio et al., 2009). Along the Tyrrhenian side, similar sequences are composed of Pliocene–Pleistocene silty-clays with sandy-conglomerates layers. However, these sequences were deposited in marine and fluvial-lacustrine environments within extensional tectonic basins, which are roughly northwest-southeast, and are elongated parallel to the chain axis (Pascucci et al., 2007).

The regional uplift induced the landscape initiation and evolution after the emersion from the marine environment. In contrast, the influence of local tectonic elements (faults) on the Quaternary continental deposit arrangement and on the catchment landscape and its recent evolution is limited in the piedmont and coastal hilly areas. The oldest (Middle Pleistocene–late Middle Pleistocene) alluvial deposits are affected (sometimes displaced by a few metres) in localized sectors of the Adriatic and Northern Sicily piedmont-coastal belts. In addition, although the epicentres of recent and historical earthquakes located along the Apennine piedmont and the Adriatic and Northern Sicily attest to the role of the present tectonic activity, this did not seem to produce significant changes along the slopes nor along the small catchments. The control is limited to the setting and arrangement of the hydrographic network where linear tectonic elements play a passive role (D'Alessandro et al., 2003, 2008; Miccadei et al., 2012, 2013, 2017).

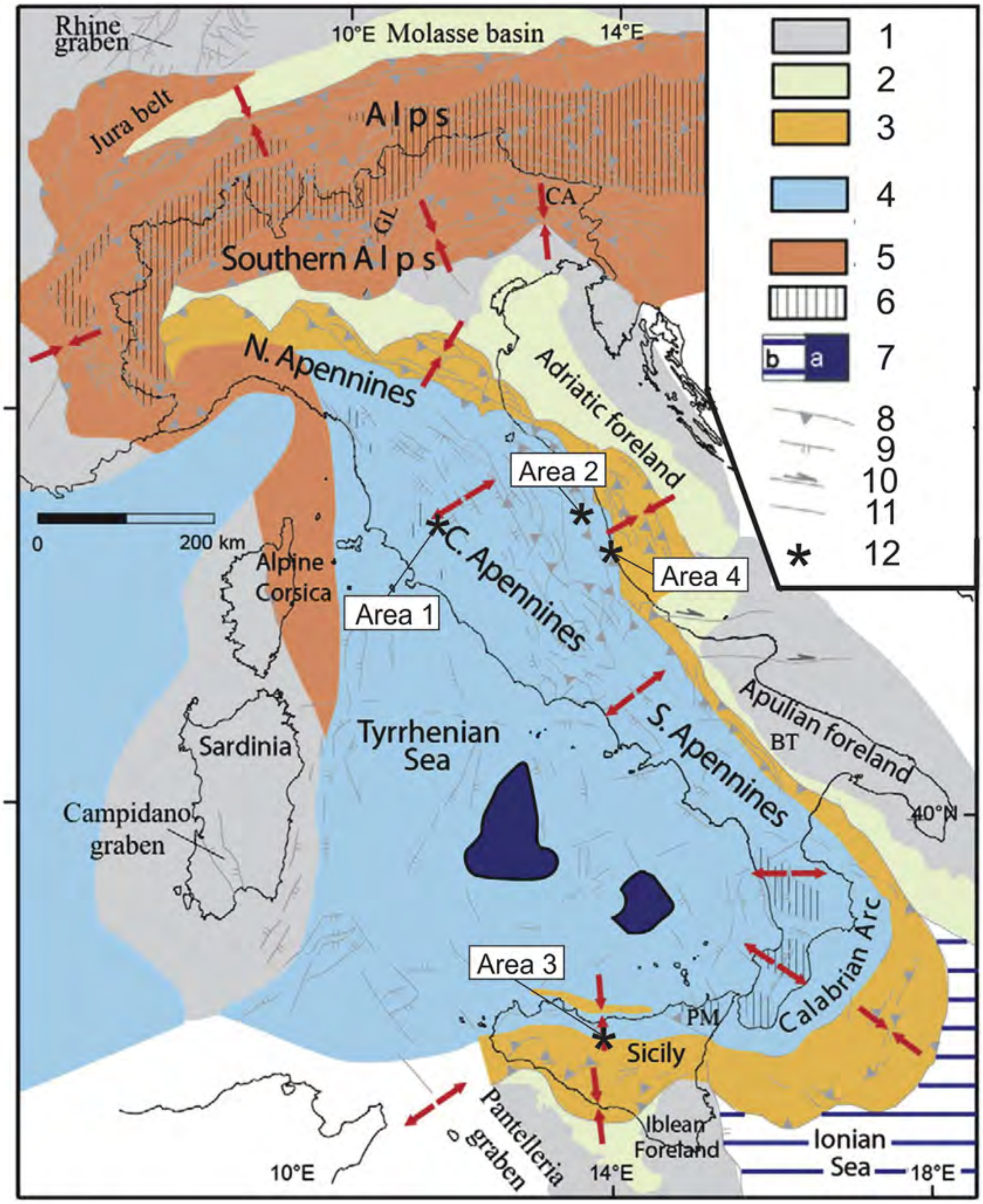


Fig. 2. Structural scheme of Italy with the location of the study areas (modified from Carminati and Doglioni, 2012). 1) Foreland areas; 2) foredeep basins; 3) compressional areas (Apennines); 4) extensional areas (Apennines); 5) Alpine thrust belt; 6) basement outcrops; 7) oceanic crust (a, Pliocene-Pleistocene; b, Mesozoic); 8) major thrusts and reverse faults; 9) major dip-slip faults; 10) major strike-slip faults; 11) undifferentiated faults; 12) study areas location.

The current landscape configuration can be attributed primarily to the Pleistocene–Holocene geomorphological dynamics because of the combined action of tectonic uplift, local tectonics, and climate change/eustasy. These produced the relative sea-level changes and local base level changes and collectively affected the landscape shaping of the inland and coastal hilly areas. About 125,000 yrs. BP, during the last interglacial period, the sea level was slightly above the current one (+6–17 m; Waelbroeck et al., 2002; Siddall et al., 2003; Lambeck et al., 2004; Ferranti et al., 2010; Antonioli, 2012). Around 20,000 yrs. BP, corresponding with the climax of the LGM, the sea level dropped down to 108–130 m below the present one, also taking the glacio-hydro-isostatic effects into account (Fig. 2; Waelbroeck et al., 2002; Siddall et al., 2003; and for Italy, Antonioli, 2012; Lambeck et al., 2004, 2011). The climate warming of the beginning of the Holocene triggered a progressive sea-level rise. This did not proceed regularly but followed phases of stasis and relative rise/fall, corresponding to the alternation of wet and dry periods. The present-day level was reached ~6000 yrs. BP, with minor subsequent oscillations (Lambeck and Purcell, 2005; Parlagreco et al., 2011; Benjamin et al., 2017).

The present climatic conditions range from the temperate to Mediterranean (Blasi et al., 2010), with some differences from north to south in terms of the rainfall amount and temperature. In the Tyrrhenian hilly area (Formone River area), the climate is temperate sub-littoral, with

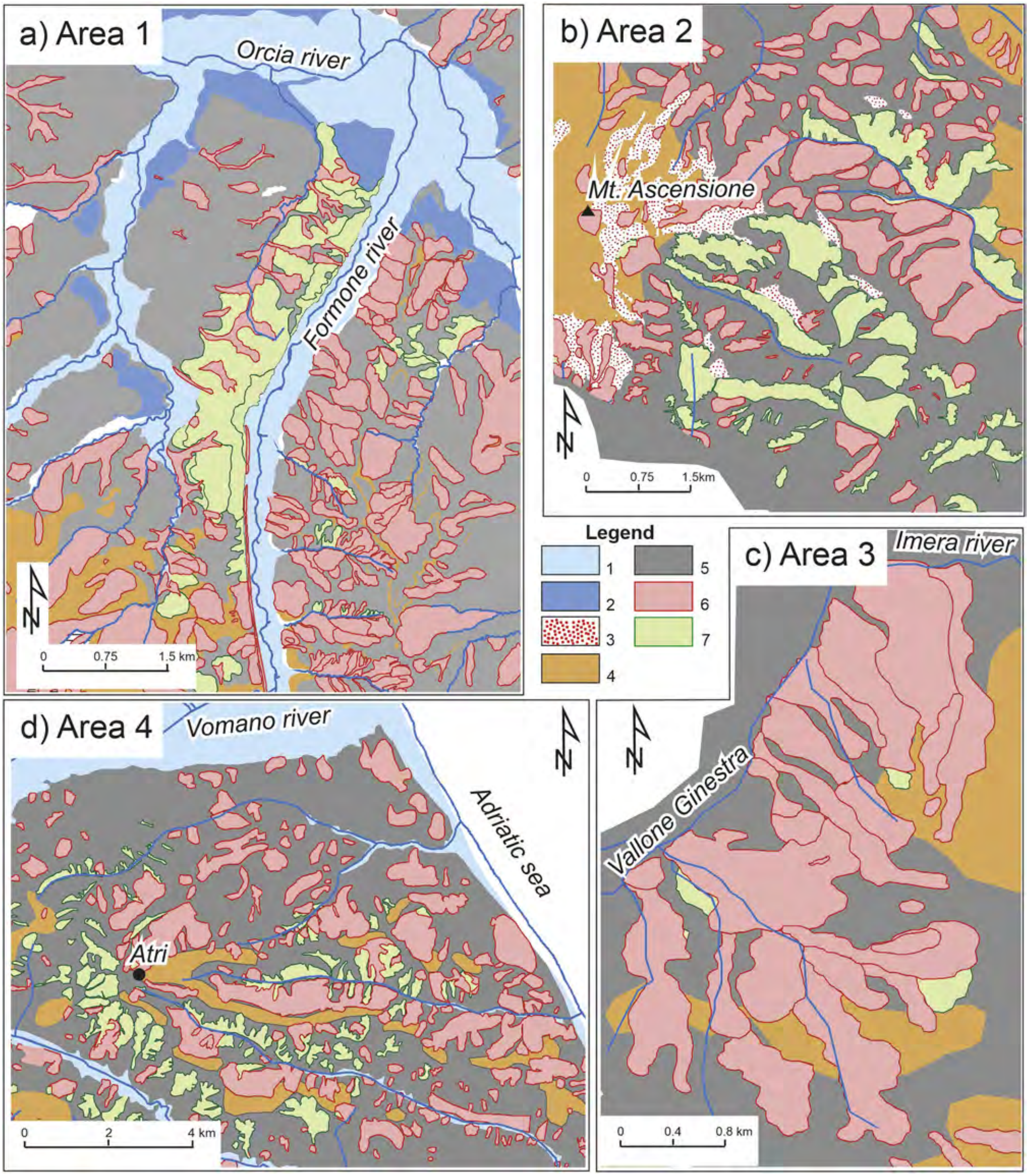


Fig. 3. Geological and geomorphological sketch of the study areas. a) area 1, Formone river; b) area 2, Mt. Ascensione; c) area 3, Imera Settentrionale river; d) area 4, Atri. Legend: 1) fluvial deposits; 2) terraced fluvial deposits; 3) slope deposits; 4) sandy-conglomeratic bedrock; 5) clayey bedrock; 6) landslides; 7) badlands.

average rainfall of approximately 970 mm/yr and two peaks in autumn and winter (Buccolini et al., 2014); temperatures are characterised by strong seasonal contrast, with the highest values in summer. The Adriatic areas (Mount Ascensione and Atri areas) have a similar climate, which is temperate sub-littoral. The annual temperatures are between 12.5 °C and 15.5 °C, and the mean annual rainfall is approximately 650 mm near the coast and 1000 mm on piedmont reliefs (Buccolini et al., 2010). Both areas are frequently affected by strong rainfall events inducing heavy soil erosion (Piacentini et al., 2018), whereas the coastal and low-hilly sectors are characterised by slight summer drought. The Sicily area (Imera Settentrionale River) has a typical Mediterranean climate, with hot, dry summers and moderately cold, poorly rainy winters. The mean annual precipitation is 680 mm, concentrated in winter between October and February. The mean annual temperature is 16

°C, with a maximum of 24 °C during summer and a minimum of 9 °C in winter (Pulice et al., 2012). In all the study areas, however, conditions of summer drought are usually followed by periods of heavy rainfall inducing intense soil erosion.

3. Methodology

An integrated approach was used in this study that combined the previously reported data with the newly collected one. Existing data for the Formone area (Buccolini et al., 2014), Atri and Mt. Ascensione areas (Buccolini et al., 2010), and Imera Settentrionale area were combined with new information from the present investigation (e.g., geomorphological surveys and markers). Finally, all information was integrated and combined to outline an evolutionary model for the small catchments of the Central Apennines and Northern Sicily piedmont for the last 20,000 years.

The detailed geomorphological features and the data on the geomorphological markers for the four study areas are presented in Sections 4 and 5, respectively. They include (i) geomorphological surveys, (ii) sampling and dating of Quaternary continental deposits, (iii) topographical and morphometrical processing, and (iv) evolutionary model development.

(i) Geomorphological investigations were performed at a medium-scale (1:50,000–1:25,000) in the broader study areas and subsequently at a detailed scale (1:10,000–1:5000) in the small catchments. The investigations were specifically focused on Quaternary continental deposits covering the clayey marine bedrock and on landforms due to gravity and runoff (e.g. landslides, badlands).

(ii) The continental deposits resulting from the geomorphological surveys were chronologically constrained using palaeosols embedded within slope and fluvial deposits. Palaeosols were radiocarbon dated using the accelerated mass spectrometry (AMS) technique (Beta Analytic Inc., Miami, Florida, U.S.A.). Through these constraints, the landscape evolution processes of the four catchments were compared and correlated. In areas where datable layers were not available, geomorphological considerations allowed the correlation of continental deposits.

(iii) Topographic and morphometric analyses were performed via processing vector topographic maps provided by the regional administrations (at 1:5000 and 1:10,000 scale) in a GIS environment (ESRI ArcGIS software, v. 10.3). For the Atri area, the surface topography was correlated to bathymetric data at different scales (F.34 of the Nautical Charts of the Italian Navy's Hydrographic Institute, 1:100,000 scale; ISPRA, 2012a, 1:50,000 scale; 1 m contours, Trincardi et al., 2014). For each area, the palaeo-topographies were reconstructed from a set of vertices corresponding to surface remnants using triangular irregular networks (TINs). Through the geomorphological and chronological correlation of the Quaternary continental deposits, the morphology during the last glacial stage (roughly 20,000 yrs. BP) was obtained for all of the study areas.

(iv) The correlation and comparison of the study areas allowed us to outline the similarities in terms of evolution of the small catchment considered. This made it reasonable to outline a broad framework of late Quaternary-Holocene small catchments' landscape evolution throughout the Central Apennine and Northern Sicily. This suggests a common evolutionary model that considers the local geomorphological features and the similarities among them.

4. Small catchments: case studies

4.1. Inland catchments

4.1.1. Formone River

The Formone River study area is in the lowermost sector of the Formone River catchment (5 km long, ~12 km^2 wide, and elevation ranging between 300 m and 600 m a.s.l.) up to the confluence with the Orcia River (Fig. 4). The bedrock is composed of marine sediments consisting of laminated clay overlaid by sandy-conglomeratic units. The sedimentary sequence is arranged into a homocline configuration. The superficial continental deposits mainly comprise sandy-gravelly fluvial deposits covering the valley floor, whereas on the valley sides, patches of thin fluvial and colluvial deposits, including palaeosol levels, are locally preserved on strath terraces (i.e., bedrock benches fluvially eroded and occasionally overlain by thin covers of fluvial sediment). Near the confluence with the Orcia River, fluvial terraces on both valley sides of the Formone catchment can be correlated to the Orcia late Pleistocene fluvial terraces (Buccolini et al., 2014). Along the main Orcia River valley, four levels of fluvial terraces were recognised: the highest, 1st level, is placed 75–100 m above the current valley floor and can be attributed to the intermediate Middle Pleistocene; the 2nd level, dating back to the latest part of the Middle Pleistocene, is 40–60 m above the present valley floor; the 3rd level, dating back to the Late Pleistocene, is 15–30 m above the present valley floor; and the last terrace (4th level), attributed to the Holocene, is 10–15 m above the present thalweg (Buccolini et al., 2014 and references therein).

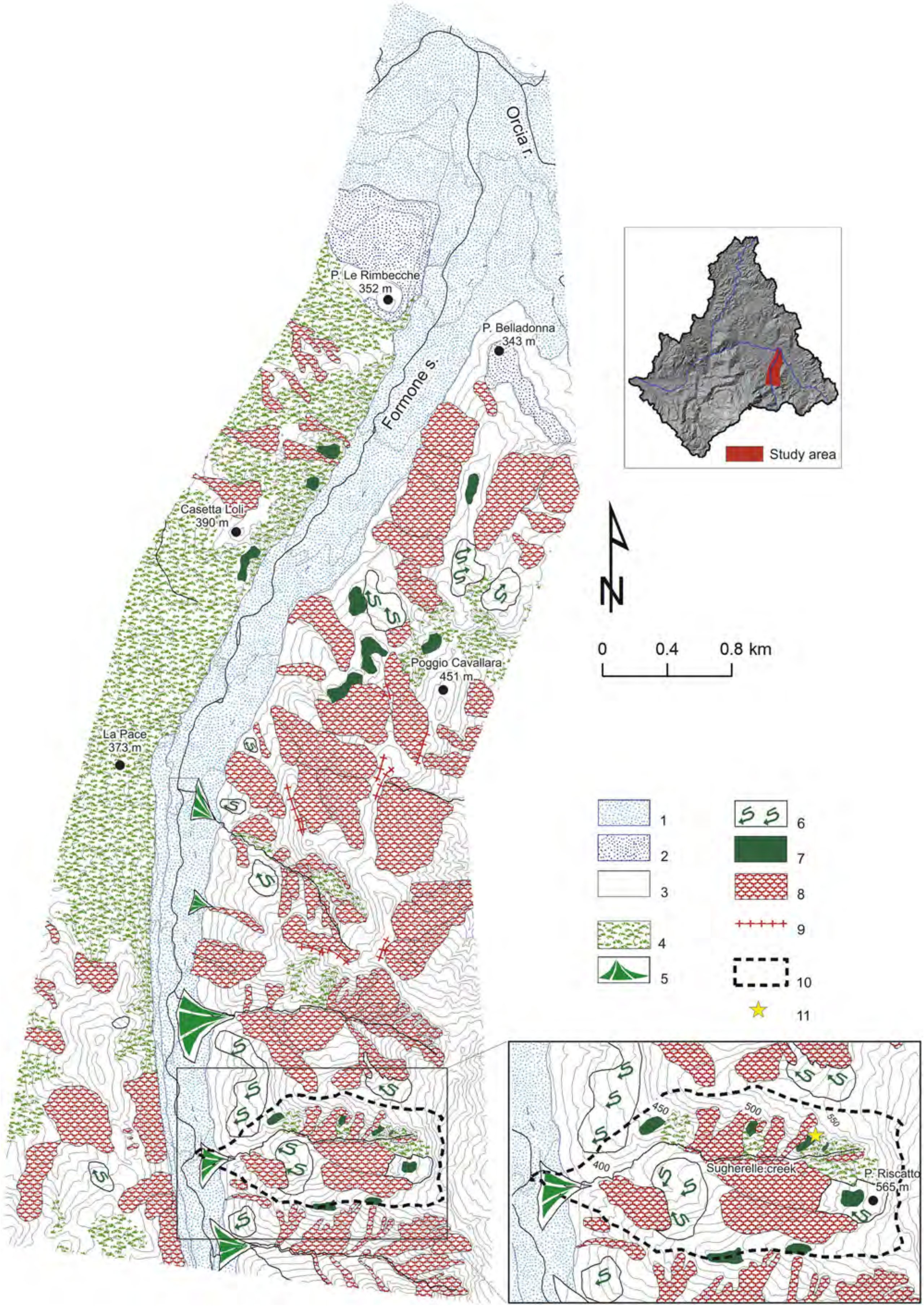
Badlands developed into the clay bedrock are often overlain by hard cap-rocks (i.e. sand-conglomerate) and are mainly present on the western side of the Formone catchment on steep slopes and within some minor tributary catchments. These landforms are presently active, with scarce vegetation cover and high erosion rates. Ciccacci et al. (2003) and Della Seta et al. (2007) reported an erosion rate of ~4–5 cm/yr derived from direct measurements. Active badlands are present mostly near the riverbed, whereas moving away from the river; they become inactive and are sometimes reshaped by agricultural practices during reclamation activities. Finally, widespread landslides (mostly flows and rotational slides), both active and dormant and shallow to >10 m deep, affect the steep slopes on the eastern riverside. Along the watershed divides or in the uppermost part of the slopes, strath terraces are present, occasionally covered by thin patches of sandy-gravelly fluvial/colluvial deposits.

4.1.2. Mount Ascensione

Mount Ascensione (1181 m a.s.l.) is the highest relief of the peri-Adriatic piedmont (Fig. 5). It consists of a lithic bedrock composed of a thick sequence of several sandy and sandy-clayey levels that overlie a basal conglomeratic unit (Upper Pliocene), interbedded with closely stratified clays. It is arranged in a cuesta-like homocline relief, with strata dipping 15°–20° towards E-NE and widely outcropping along its southern and eastern slopes (Cantalamessa and Di Celma, 2004). The area includes two small catchments for a total area of 22 km^2.

The slopes of Mount Ascensione are covered by a thick stratified slope deposit, whose top surface represents a unique example of a pediment (glacis) in the hilly piedmont of the Apennines chain. This deposit comprises alternating sand (predominant) and gravel (secondary) and is weakly cemented and with evident onwards clinostratification, with

Fig. 4. Geomorphological sketch of the Formone river area (location in the upper right inset and in Fig. 1). Legend: 1) fluvial deposits (Holocene); 2) terraced fluvial deposits (Middle Pleistocene-Late Pleistocene); 3) mainly pelitic bedrock (Pliocene-Pleistocene); 4) badlands; 5) alluvial fan; 6) solifluction processes; 7) strath terrace; 8) landslides; 9) gravitational trench; 10) Sugherelle catchment; 11) sampling site. In the lower right inset, a close-up of the Sugherelle catchment map.


Orcia r.
Formone s.
P. Le Rimbecche
352 m
P. Belladonna
343 m
Casetta Loli
390 m
Poggio Cavallara
451 m
La Pace
373 m
Study area
0
0.4
0.8 km
1
2
3
4
5
6
7
8
9
10
11
450
500
550
400
Sugherelle creek
P. Riscatto
565 m

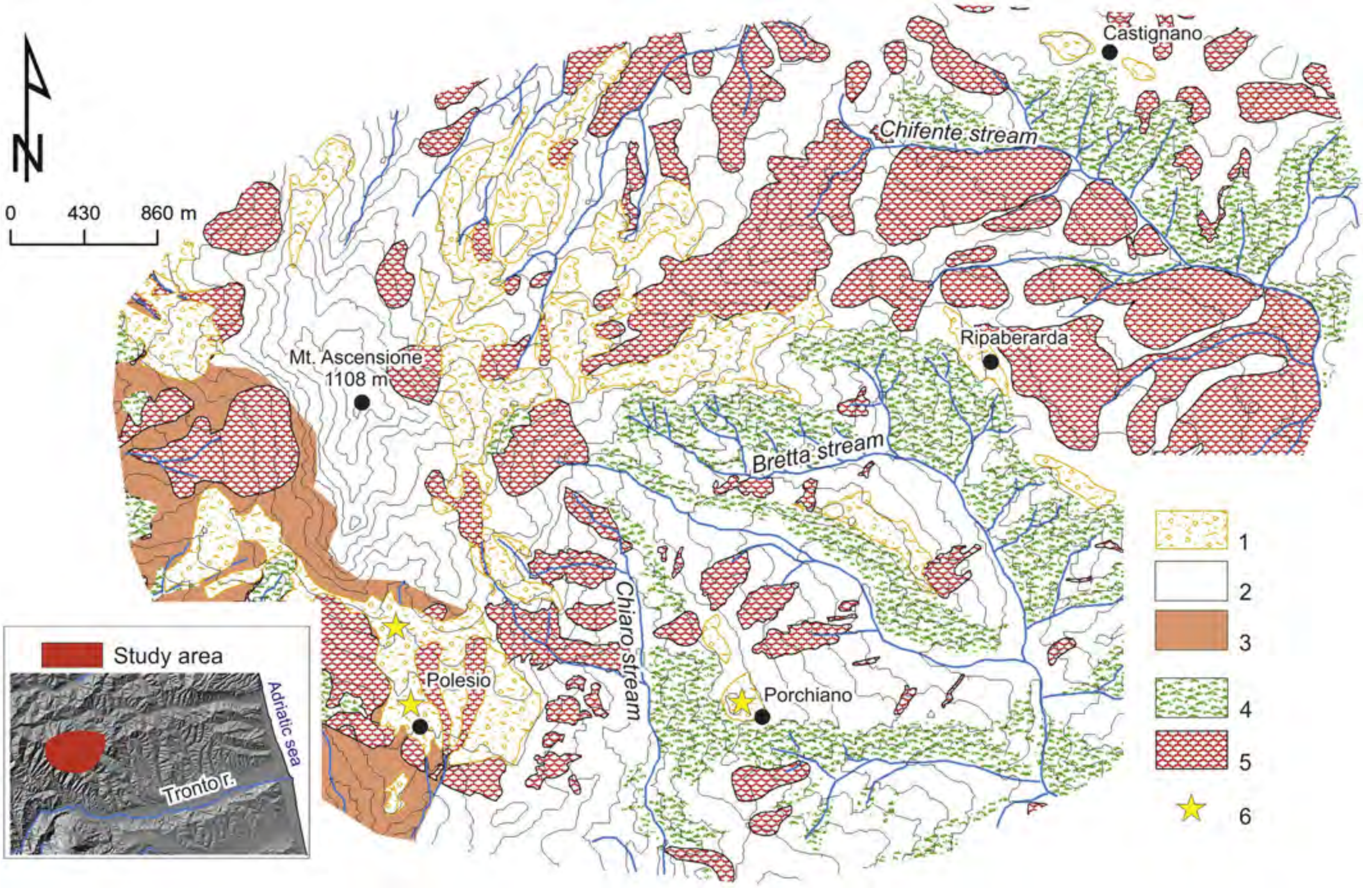


Fig. 5. Geomorphological sketch of the Mt. Ascensione area (location in the lower left inset and in Fig. 1). Legend: 1) slope deposits (Middle Pleistocene – Late Pleistocene); 2) mainly clayey and conglomeratic bedrock (Early Pliocene); 3) mainly clayey-sandy bedrock (late Messinian); 4) badlands; 5) landslides; 6) sampling site.

dipping strata ranging between 12° and 15° in the upslope portion and sub-horizontal in the middle and downslope sector. Locally, medium-fine to very fine yellowish sands are present on the top. Within the sequence, some browns palaeosols 20–50 cm thick are present. These deposits, deeply incised by fluvial and gully erosion or badlands, have been attributed to the Middle Pleistocene, the "Villafranchian", or the end of Middle Pleistocene (Castiglioni, 1935; Demangeot, 1965; Dramis et al., 1982; Centamore and Deiana, 1986). More recently, Gentili et al. (1998) and Buccolini et al. (2010), through detailed geomorphological analyses and radiocarbon dating, recognised two generations of slope deposits, which were attributed to the Middle Pleistocene and late Pleistocene.

On the clayey bedrock and specifically on anti-dip slopes, spectacular badlands are present, while mass movements mainly affect dip slopes (e.g., Dramis et al., 1982; Buccolini et al., 2007). The main valley (Tronto River) hosts fluvial deposits, arranged in four levels of terraces from Middle Pleistocene (1st level, ~150 m above the current valley floor) to latest part of the Middle-beginning of Late Pleistocene (2nd level, ~80 m above the present valley floor) and Late Pleistocene (3rd level, ~30 m above the present valley floor). A Holocene terrace completes the sequence (4th level, ~10 m above the present valley floor; Coltorti et al., 1991; Della Seta et al., 2008).

4.1.3. Imera Settentrionale

This area includes the Vallone Ginestra, a small catchment, which is the south-western tributary of the Imera Settentrionale River (Fig. 6). It encompasses ~4.8 km^2 with elevations ranging from 950 m on the drainage divide to 450 m at the valley bottom. Steep slopes (up to >50°) characterise large portions of the valley sides. The bedrock mainly consists of a marine sequence (Cretaceous-Messinian), which includes sandy clay and mudstone, sandy mudstone, sandstone, clayey sand, conglomerate, and coarse sand, in stratigraphic succession from the bottom to the top (Agnesi et al., 1999). Quaternary continental deposits are very poorly preserved in the small catchment, consisting of small and thin patches of colluvial deposits on the slopes and Holocene fluvial-colluvial deposits in the valley floor, whereas the oldest fluvial deposits are not preserved at all. However, along the main valley (Imera Settentrionale River) and particularly in the lower sector, three levels of fluvial terraces and related deposits can be detected. Their elevation above the present valley floor ranges from >100 m (1st level) to 5–7 m (3rd level). Their ages range from Middle Pleistocene (1st level) to Late Pleistocene (3rd level; Di Maggio et al., 2009).

In addition, in this area, the main geomorphological processes are related to soil erosion and gravity. Among the main landforms, gullies up to 5–10 m deep are largely present, mainly affecting the low gradient N-facing slopes. Extensive landslides (mostly flows and rotational slides) affect almost the entire eastern valley side with sizes reaching several hundreds of square metres.

4.2. Coastal catchments

4.2.1. Atri area

In the Atri area, two small coastal catchments were investigated: the Calvano stream basin (34 km^2) Cerrano Stream basin (15 km^2) (Fig. 7). The outcropping lithologies consist of Pleistocene bedrock units and Upper Pleistocene–Holocene superficial continental deposits. The bedrock comprises a marine succession composed of clayey-marly deposits arranged in centimetric layers, coarsening upwards and passing into a

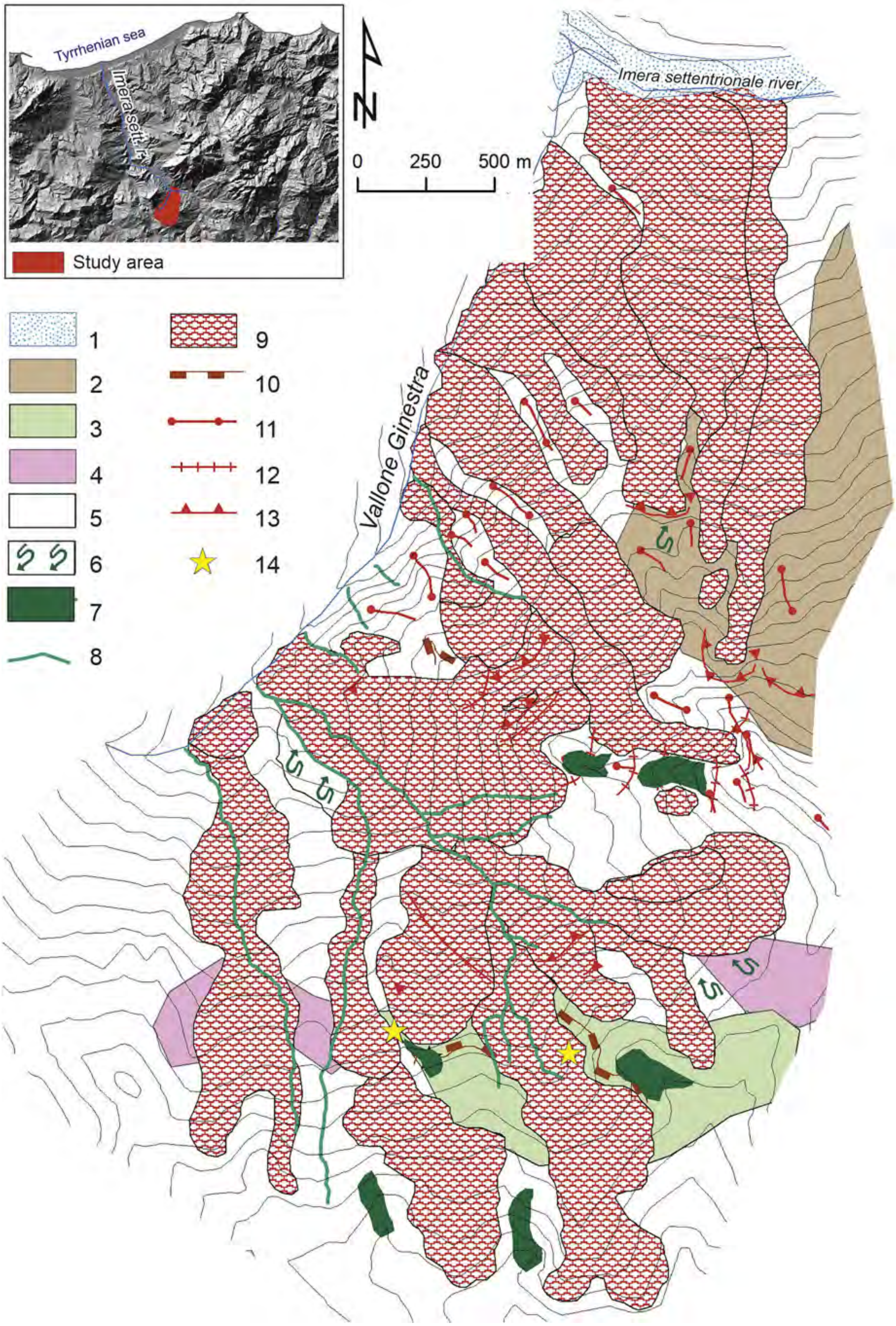


Fig. 6. Geomorphological scheme of the Imera river area (location in the upper left inset and in Fig. 1). Legend: 1) fluvial deposits (Holocene); 2) arenaceous-conglomeratic bedrock (Pliocene-Pleistocene); 3) mainly clayey-sandy bedrock (Oligocene-Miocene); 4) marly-clayey bedrock (Cretaceous-Paleocene); 5) mainly conglomeratic-pelitic bedrock (Tortonian-Messinian); 6) solifluction processes; 7) strath terrace; 8) gully; 9) landslides; 10) structural scarps; 11) sharp ridges; 12) trenches; 13) landslides scarps; 14) sampling sites.

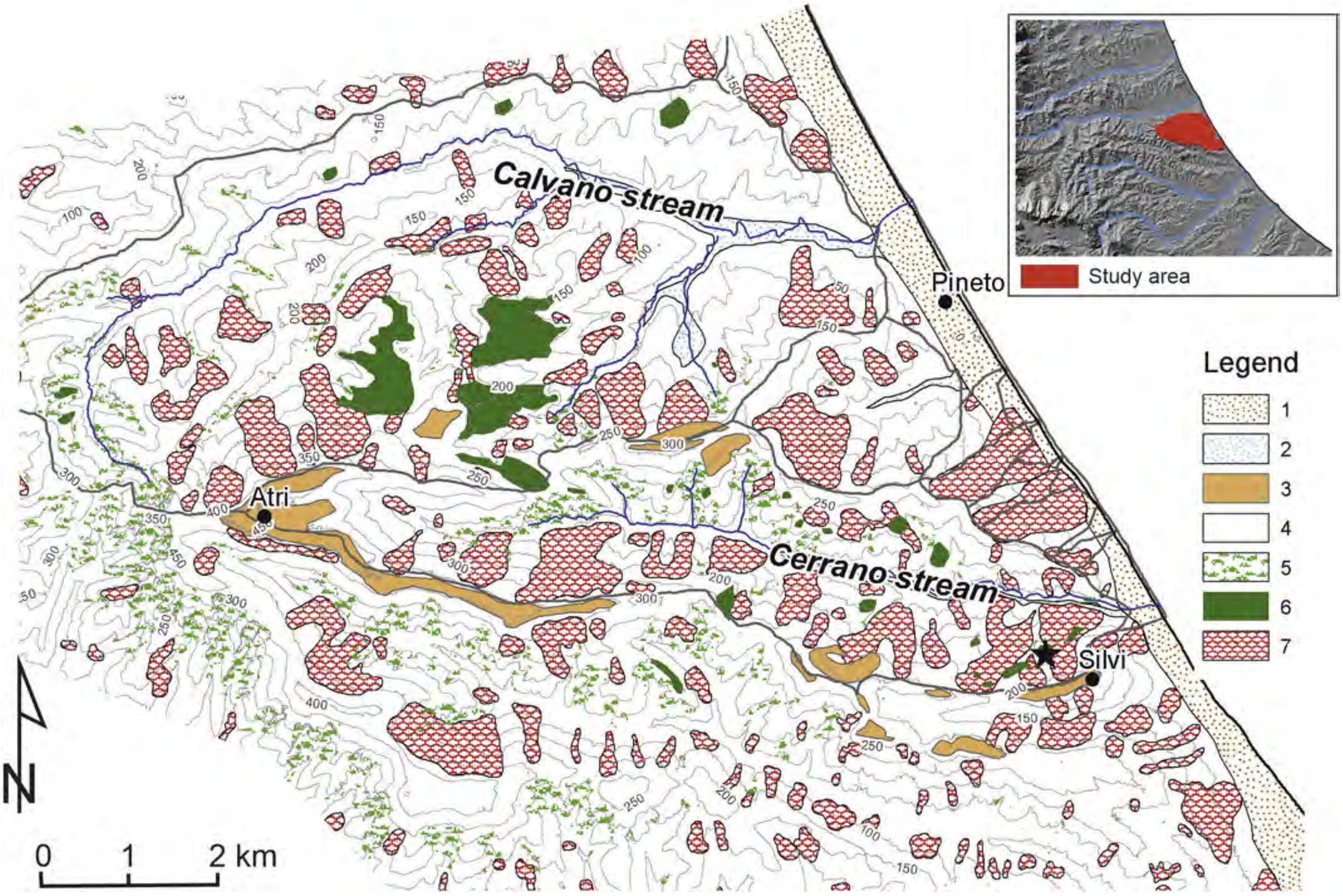


Fig. 7. Geomorphological sketch of the Atri area (location in the upper right inset and in Fig. 1). Legend: 1) beach and coastal deposits (Holocene); 2) fluvial deposits (Holocene); 3) sandy-conglomeratic bedrock (Early-Middle Pleistocene); 4) clayey bedrock (Early Pleistocene); 5) badlands; 6) strath terraces; 7) landslides.

regressive sequence of sandy clay, sand, sandstone, and conglomerate. The latter marks the transition from marine to continental environments. The conglomerates mainly outcrop along the watershed divides, with sand, and sandstone along the surrounding scarps, and clay units along the valley sides and bottom. Quaternary superficial continental deposits are frequent on the slopes and in the valley bottom and mainly consist of thin sand-gravel slope deposits and clay-silt-sand eluvial-colluvial deposits, and locally, of small remnants of gravel-sand fluvial deposits. The structural arrangement of the bedrock is a regular homocline with strata from horizontal to gently (up to 10°) dipping towards the northeast.

From a morphostructural perspective, a "plateau" morphology defines the hilltops. It is set on the sandstone-conglomerate bedrock units, at an elevation ranging from 250 m to 450 m a.s.l. This surface is cut by roughly east-west streams (i.e. Calvano and Cerrano streams) located between the sea mouths of the main rivers (i.e. Vomano River and Saline River). The resulting symmetrical valleys are characterised by landslides and a dense drainage network, including widespread badland areas. Towards the coastline, the interfluves are cut off by steep coastal slopes, affected by large landslides, at the bottom of which lies a narrow sandy beach and the coastal plain, with a total width of approximately 500 m. The river valleys of the Vomano and Saline Rivers are filled with fluvial deposits, which form four levels of terraces: the 1st level (Middle Pleistocene) lies at ~100 m above the present valley floor; the 2nd level (latest part of Middle Pleistocene) at approximately 40–50 m; the 3rd level (Late Pleistocene) approximately 15–20 m; and the 4th level (Holocene) approximately 4–6 m (ISPRA, 2012a, 2012b).

The main landforms corresponding to the short-term and long-term evolution of the basins are due to gravity-induced (flows and rotational landslides) and runoff processes (rills, gullies, badlands) (Buccolini et al., 2007; Buccolini and Coco, 2010). Badlands affect the steep clayey hillslopes, often with conglomeratic cap-rock (mostly south-facing).

5. Geomorphological markers

In the four study areas, geomorphological markers were defined, consisting of slope and fluvial deposits, including palaeosols and charcoal fragments. These deposits were sampled on pediment surfaces and strath terraces along the slopes. They were dated back to different intervals of the late Pleistocene with radiocarbon dating providing insight and constraints for the geomorphological evolution of the basins.

5.1. Inland catchments

5.1.1. Formone River

In the Formone River area, the marker consists of a palaeosol found within the fluvial deposits preserved on strath terraces (Fig. 4). This palaeosols located near the drainage divide of the Sugherelle catchment, a small (0.78 km^2 wide, 3.9 km long) eastern tributary of Formone River (Fig. 4). The elevation within the basin ranges from 380 m to 600 m a.s.l., with a slope sometimes exceeding 50°. The detailed geomorphological and geopedological surveys carried out in previous studies (Buccolini et al., 2014) documented several sub-horizontal strath terraces or gently dipping pediments near the drainage divide, often covered with thin and small remnants of

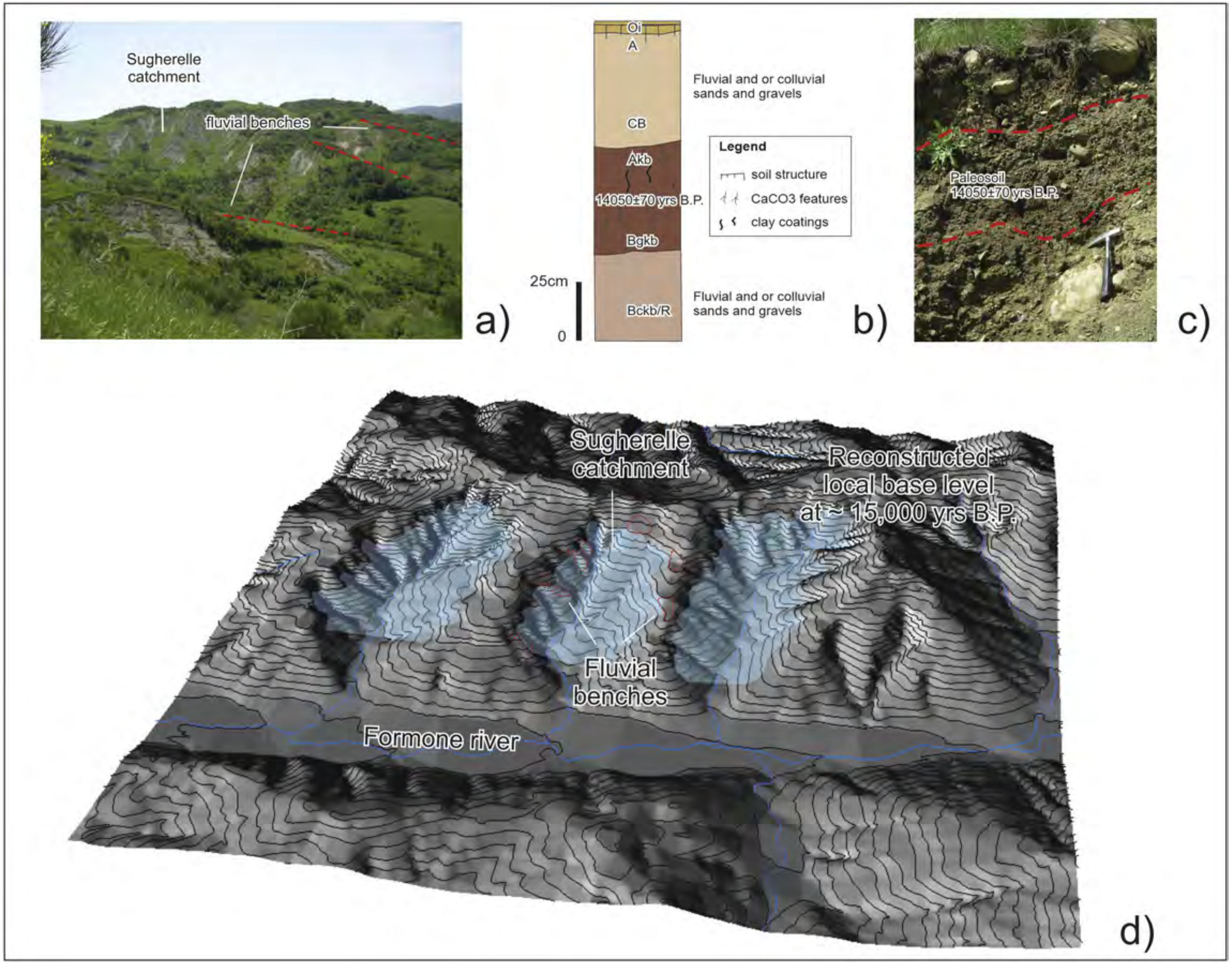


Fig. 8. Geomorphological markers in the Sugherelle catchment: a) panoramic view with location of the strath terraces used for the chronological reconstruction; b) schematic stratigraphic log of the sampling site; c) detail of the dated paleosoil; d) schematic block diagram showing the morphological setting of Formone river at ~20,000 yrs. B.P.

fluvial deposits (Fig. 8a). Within one of these, a brownish buried palaeosol, >40 cm thick, containing organic matter was found (Fig. 8b,c). AMS radiocarbon dating of a charcoal fragment from the buried A horizon yielded an age of 14,050 ± 70 yrs. B.P. (Beta-273354, Beta Analytic Inc., Miami-FL, USA), indicating the end of the Late Pleistocene. Based on geomorphological correlations, the surface remnants having similar features can be dated back to the same age. A possible Late Pleistocene palaeosurface was processed and reconstructed in a GIS environment (Fig. 8d). This palaeosurface can be geomorphologically correlated to the Late Pleistocene alluvial deposits preserved in both the eastern and western side of the Formone River (Buccolini et al., 2014) and connected to the Orcia River terraces near the confluence at an elevation of ~300 m a.s.l. The incision of this surface led to the present Formone River configuration.

5.1.2. Mount Ascensione

The main geomorphological markers and constraints in the Ascensione area are given by the remnants of thick stratified slope deposits laying over ancient pediments (Fig. 9a) as already documented (Buccolini et al., 2010). The radiocarbon dating of three brown palaeosols (20–50 cm thick and placed at different levels within the sequence) evidenced two different units of slope deposits (Gentili et al., 1998; Buccolini et al., 2010) (Fig. 5). The older one is located between 700 and 850 m a.s.l. and dated back to 41,640 ± 1260 yrs. BP (Beta-108532, Beta Analytic Inc., Miami-FL, USA); the two younger ones are located between 420 and 800 m a.s.l. and dated back to 23,230 ± 170 yrs. BP (Beta-108531, Beta Analytic Inc., Miami-FL, USA) and 22,680 ± 170 yrs. BP (Beta-108530, Beta Analytic Inc., Miami-FL, USA) (Fig. 9b,c). The end of the sedimentary cycle should be even more recent, considering that the stratigraphic position of the younger sample is not on the top of the deposits and the sedimentation rate was estimated at around 1.5 mm/yr (Buccolini et al., 2010). The distribution of the remnants of the deposits allowed the reconstruction of the original deposit distribution and the top surface (Fig. 9d), extended approximately 10 km^2 around the Mount Ascensione between 400 m and 850 m a.s.l., with a roughly 5-km maximum distance from the top (Buccolini et al., 2010). These deposits infilled a previously eroded

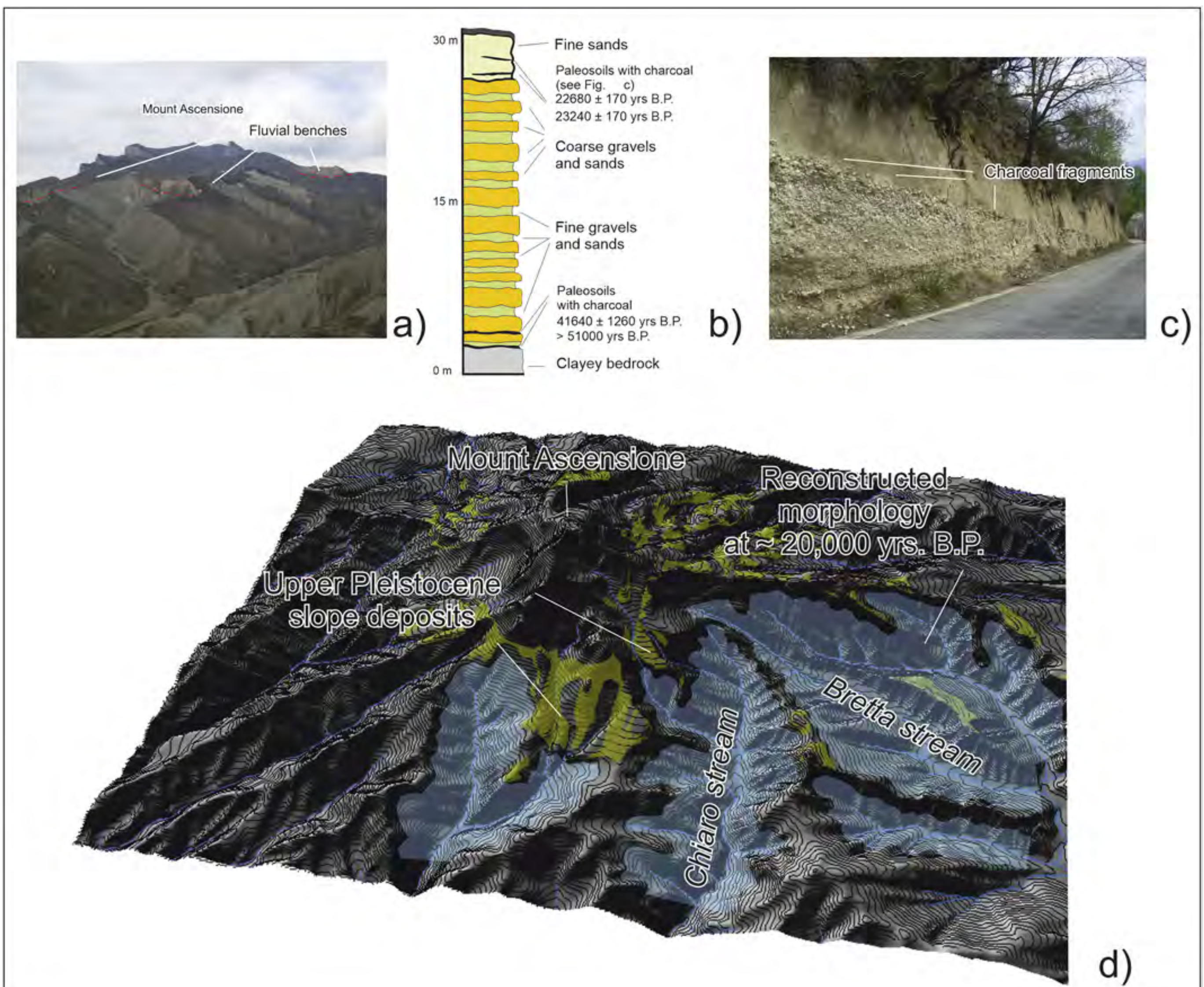


Fig. 9. Geomorphological markers in the Mount Ascensione area: a) panoramic view with location of the strath terraces used for the chronological reconstruction; b) schematic stratigraphic log of the sampling sites; c) detail of one of the sampling sites; d) schematic block diagram showing the morphological setting of the Mount Ascensione area at ~20,000 yrs. B.P.

landscape that was incised almost entirely into the clayey bedrock and subdivided in small valleys (tens of metres deep and hundreds of metres wide) separated by narrow interfluves. Currently, the deposits are connected to the Ascensione slopes in the upper sector and are progressively incised into the medium-high sectors. Downstream, they are transversely and/or longitudinally truncated (Polesio) or preserved as small and thick isolated remnants (Porchiano) (Fig. 5).

5.1.3. Imera Settentrionale River

The primary geomorphological markers of the Imera Settentrionale River area (Vallone Ginestra small catchment) are provided by narrow strath terraces placed along the main drainage divide between 720 m and 750 m a.s.l (Figs. 6 and 10a). These terraces are only occasionally covered by thin gravel colluvial deposits (Fig. 10b,c), derived from the erosion of the conglomerates of the bedrock sequence, whose depositional surface is related to a pediment-like landform. Different from the other areas, no datable levels were found within the deposits. Nevertheless, a unique erosion surface was reconstructed by geomorphologically correlating the strath terraces within the Vallone Ginestra. Considering its morphologic configuration, this surface can be related to the Late Pleistocene fluvial terrace of the Imera Settentrionale River. According to this correlation, the erosion surface can be dated at the end of Late Pleistocene. Similar surfaces were not identified at intermediate altitudes, which suggests a rapid evolution of the drainage system from an elevation corresponding to the main drainage divides.

5.2. Coastal catchments

5.2.1. Atri area

In the Atri area, discontinuous remnants of fluvial erosion surfaces and deposits show similar distribution in both catchments and are closely correlated (elevation, geomorphological features) to each other (Figs. 7, 11a). This arrangement allowed us to outline distinct strath terraces (see also Buccolini et al., 2010). Some of them can be related to the bedrock structure (e.g., located at the boundary between the sandy-conglomeratic and the clayey units), whereas some others are not and are interpreted as the remnants of former wide and flat valley bottoms (Buccolini et al., 2007). In many cases, the accumulation of slope,

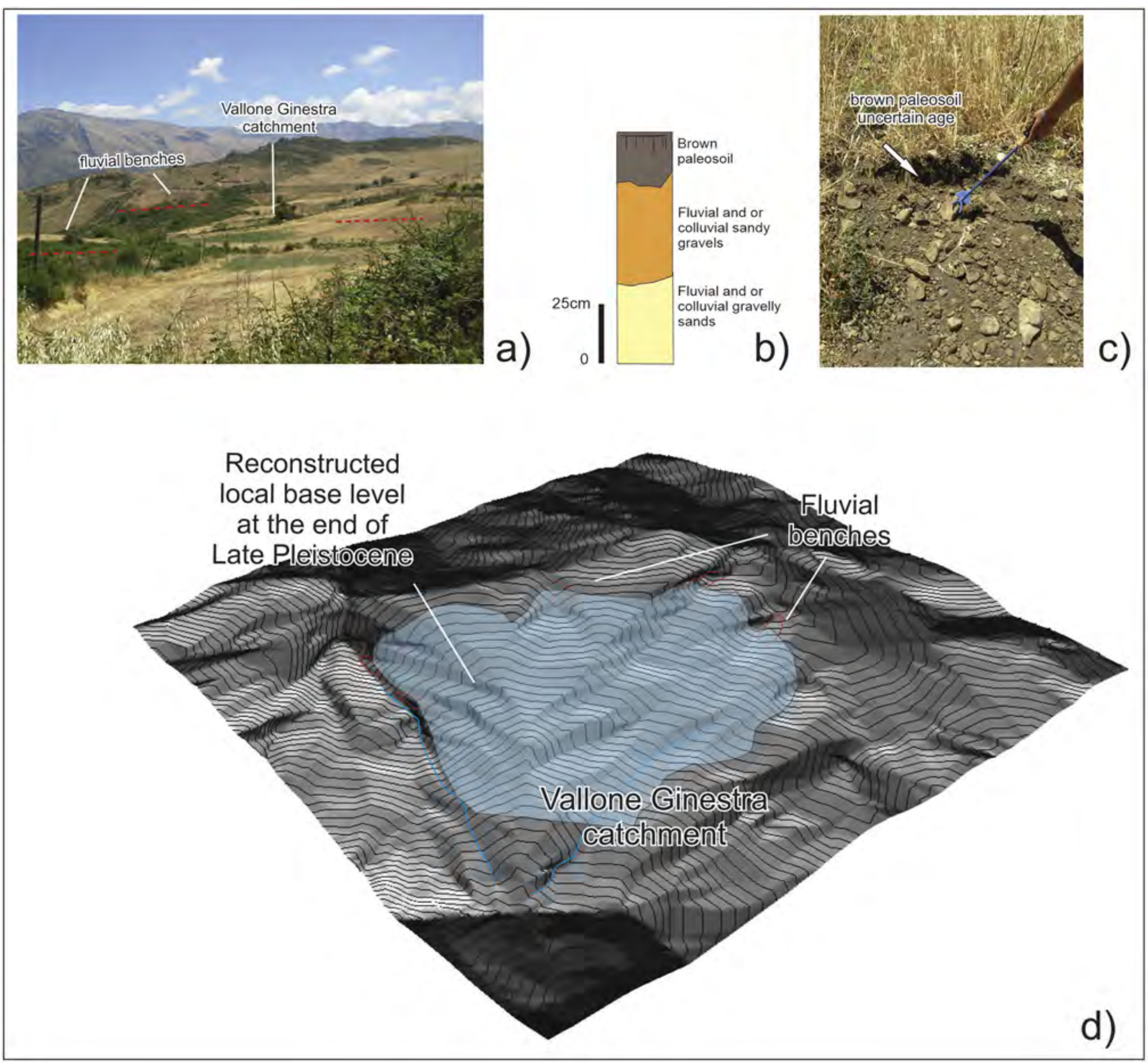


Fig. 10. Geomorphological markers in the Vallone Ginestra small catchment (Imera settentrionale area): a) panoramic view with location of the strath terraces used for the chronological reconstruction; b) schematic block diagram showing the morphological setting of the small catchment at ~20,000 yrs. B.P.

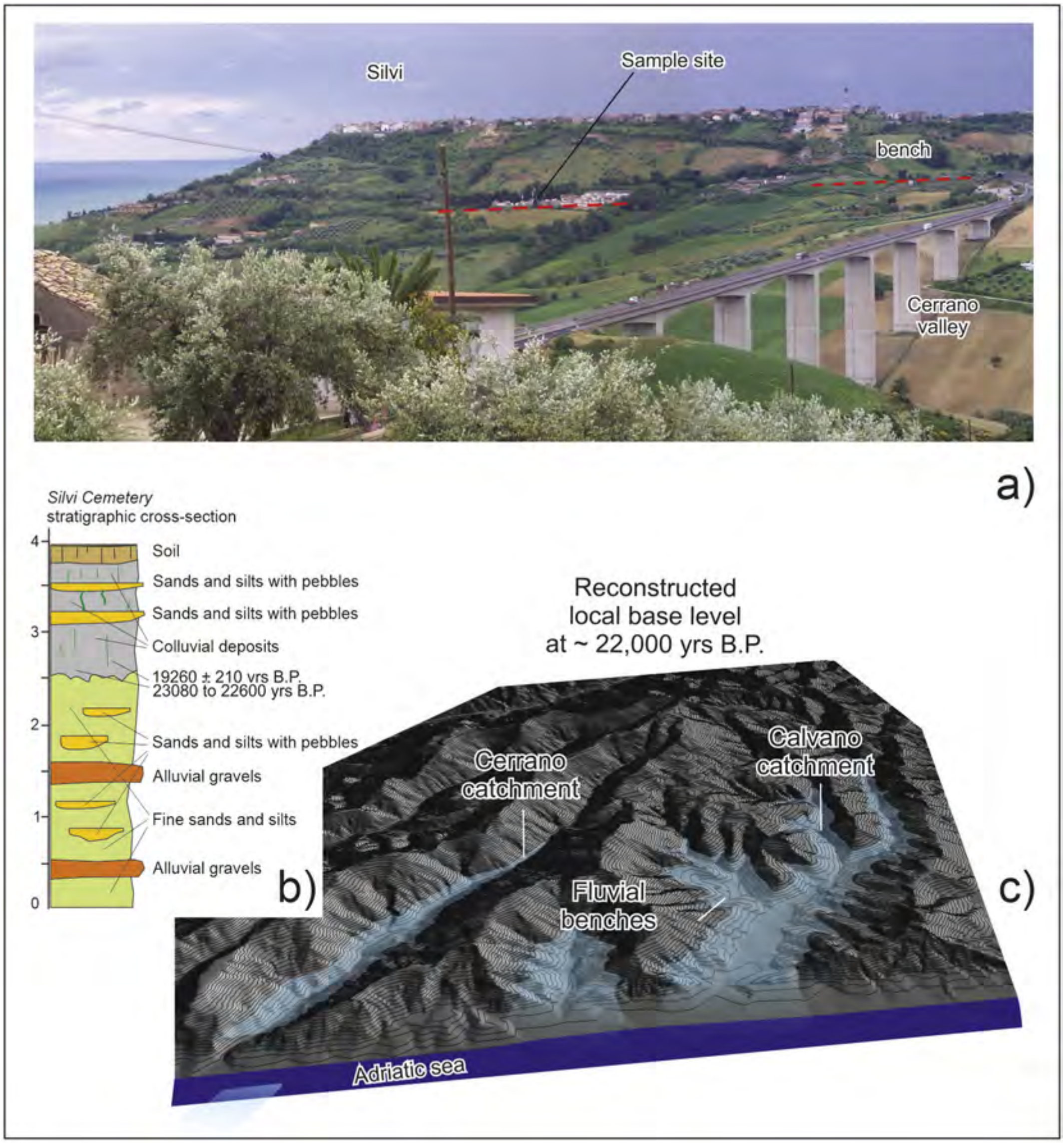


Fig. 11. Geomorphological markers in the Atri area: (a) panoramic view of the Cerrano valley (southern valley side), with evidence of the strath terraces and location of the sampling site; (b) stratigraphic log of the sampling site; (c) schematic block diagram showing the reconstruction of the paleo-valleys in the Atri area at ~20,000 yrs. B.P.

colluvial, and fluvial sediments along the terraces was observed. The radiocarbon dating of gravel sandy fluvial sediments on one of the main terraces along the Cerrano Stream (located at 125 m a.s.l.) provided an age from 22,840 ± 240 yrs. BP to 19,260 ± 210 yrs. BP (Beta-192039, Beta-192040, Beta Analytic Inc., Miami-FL, USA; Fig. 11b). The strath terraces were correlated, and a unique surface, that can be interpreted to be a palaeovalley (dating back to around 20,000 years), was reconstructed at elevations from 110 m to 140 m a.s.l. (Fig. 11c).

6. Discussion

The four study areas are typical examples of the clayey hilly landscape of Central Italy and Northern Sicily, along the piedmont of the Apennines chain, and represent two different categories of small catchments: A) inland catchments, which are tributaries of the main river valleys and are usually located some tens of km from the coastline (i.e., the Formone River, tributary of the Orcia River, Area 1; the small catchments in the Mount Ascensione area, tributaries of the Tronto River, Area 2; the Vallone Ginestra, tributary of the Imera Settentrionale River, Area 3; Fig. 1); B) coastal catchments, flowing directly to the coastline (i.e., the Calvano and Cerrano streams in the Atri area, Area 4; Fig. 1). In each area, the geomorphological data were combined with the morpho-chronological ones to understand the Late Pleistocene–Holocene geomorphological evolution and incision of the small catchments in the clayey hilly landscape of the Apennine piedmont from Central Italy to Sicily (Table 1). The correlation of the results in each area (Table 1) suggested that the two categories of catchments experienced comparable evolution. However, based on their different morphostructural settings, it can be concluded that these were affected by different controlling factors. Here, the evolution of the two types of catchments from the end of Late Pleistocene to the Holocene is summarised.

At the end of the Late Pleistocene, the clayey hills comprised a low gradient landscape with well-developed fluvial deposits in the major valleys (now preserved as the last main fluvial terrace; Coltorti et al., 1991; Della Seta et al., 2008; D'Alessandro et al., 2008; Nesci et al., 2012; Miccadei et al., 2012, 2013) and low gradient minor valleys and slopes were covered by thin fluvial and colluvial-slope deposits (now preserved on strath terraces over the clayey bedrock). During the sea-level lowstand, the coastal catchments were under similar conditions, while the coastline was up to some tens of kilometres downstream from the present one. This arrangement relates to the Late Pleistocene

Table 1
Summary of the morphological, geological, geomorphological and climatic features of the study areas.

	Area - Formone River (S Tuscany)	Area 2 - Ascensione (SE Marche)	Area 3 - Imera Settentrionale (N Sicily)	Area 4 - Atri (NE Abruzzo)
Geological framework	Uplifted extensional tectonic basins of the Tyrrhenian piedmont of the Apennines	Cuesta landscape on uplifted compressional/extensional Adriatic Apennines piedmont	Homocline landscape on wedge-top basins on the N Sicily thrust belt, filled by the terrigenous sediments	Mesa-plateau landscape on uplifted compressional/extensional Adriatic Apennines piedmont
Morphology				
Area	17.5 km^2–0.77 km^2	22 km^2	5.6 km^2	15.3–39,5 km^2
Elevation	290–610 m a.s.l.	220–1100 m a.s.l.	460–940 m a.s.l.	0–450 m a.s.l.
Hydrography	Deeply incised drainage net	Deeply incised drainage net	Deeply incised drainage net	Deeply incised drainage net
Climate	Temperate sublittoral	Temperate Sublittoral	Mediterranean	Temperate Sublittoral
Av rainfall	970 mm/yr	1000 mm/yr	500 mm/yr	650 mm/yr
Rainfall intensity	–	>100 mm/d, >40 mm/h	–	>100 mm/d, >40 mm/h
Temperature	4.5 °C Jan–21.7 °C Jul (Av. 12.5 °C)	3.5 °C Jan–21.2 °C Jul (Av. 11.1 °C)	6.1 °C Jan–22.6 °C Aug (Av. 14.1 °C)	10 °C Jan–25 °C Jul (Av. 17.8 °C)
Litology				
Bedrock	Marine silty-clayey units (Upper Pliocene)	Clay with thick conglomerate levels, sandy and sandy-clayey levels (Lower-Middle Pleistocene)	Sequence of sandy clays and mudstones, sandy mudstones, sandstones and clayey sands, conglomerates, and coarse sands.	Clay-sand-sandstone-conglomerate marine regressive Lower-Middle Pleistocene sequence.
Superficial deposits	Fluvial deposits arranged in 4 terraces (main valleys); remains of colluvium (at watershed divides)	Thick slope deposits (glacis). Fluvial deposits arranged in 4 terraces (main valleys); colluvial, alluvial and landslide deposits (minor valleys)	Fluvial deposits arranged in terraces (main valleys); poor colluvial and landslide deposits (minor valleys)	Fluvial deposits arranged in terraces (main valleys); colluvial and landslide deposits (minor valleys)
Tectonics	Pliocene-Pleistocene extensional tectonics/uplift. Horizontal or gently dipping layers	Miocene-Pliocene compression, Middle-Upper Pleistocene uplift. Homocline 20–25° NE dipping	Miocene compression and thrust system, Late Miocene thrust top basins. Homocline gently N dipping	Pliocene-Lower Pleistocene compression, Middle-Upper Pleistocene uplift. Homocline 5–10 NE dipping
Landforms	Biancane and calanchi, fluvial terraces, landslides	*Glacis* remnants, Calanchi, landslide	*Glacis* remnants, Calanchi, landslides	Gently NE dipping structural surface, Calanchi badlands, landslides
Erosion rates	0.9 mm/yr (badlands)	7.8–15.6 mm/yr	Not defined	2.5–6 mm/yr
Constraints	Paleosoil 1: 14,050 ± 70 yrs. BP	Slope deposits 41,640 ± 1260 yrs. BP 23,230 ± 170 yrs. BP 22,680 ± 170 yrs. BP	Not defined	Fluvial-colluvial surfaces 17,650 ± 100 yrs. BP 19,260 ± 210 yrs. BP
Sources	Pascucci et al., 2007; Martini et al., 2013; Buccolini et al., 2014; Ciccacci et al., 2003; Della Seta et al., 2007	Bigi et al., 1995; Buccolini et al., 2007, 2010	Agnesi et al., 1999; Abate et al., 1999; Di Maggio et al., 2009; Pulice et al., 2012	Bigi et al., 1995; Cantalamessa and Di Celma, 2004; Buccolini et al., 2007, 2010

cold stage, during which the main valleys experienced depositional processes supported by a large production of debris, while the valley sides were mostly affected by erosional and local depositional processes because of the poor vegetation cover in the cold climate (rhexistasy conditions; Erhard, 1956). In this framework, the four study areas showed a similar arrangement with small differences.

Concerning the inland hilly catchments in the Formone River (Area 1; Fig. 12a), the erosion surface dating back to the Late Pleistocene (around 15,000 yrs. BP) can be correlated with the coeval third level terrace of Orcia River near the Formone confluence (Buccolini et al., 2014). During the LGM, the middle and upper portion of the valley featured low gradient sides, covered by colluvial and fluvial deposits that made the slope uniform. A similar situation can be assumed for Mount Ascensione (Area 2; Fig. 12a) during the Late Pleistocene (i.e., around 20,000 yrs. BP, for this area). Thick slope deposits developed in a vast pediment and filled the pre-existing erosional features in the clayey bedrock. Along the major river valleys (e.g., Tronto River), this landscape was connected to the deposition of the Late Pleistocene fluvial plain, now preserved above the present valley floor (3rd level terrace). The Imera Settentrionale River (Area 3; Fig. 12a), during the Late Pleistocene, also featured a low gradient landscape with erosional surfaces on the clayey bedrock, as supported by geomorphological evidence like strath terraces with thin colluvial covers. According to the geomorphological correlations, even without certain dated constraints, this landscape can be connected to the depositional surface of the late Pleistocene (3rd level) terrace, which is now preserved within the Imera Settentrionale valley.

Otherwise, the coastal catchments (i.e., Atri, Area 4; Fig. 12a) during the Late Pleistocene (i.e., around 20,000 yrs. BP) were directly influenced by sea-level fluctuations. At this time, the sea level was up to 130 m (LGM) below the present one. Considering a very shallow and regular bathymetry (ISPRA, 2012a; Trincardi et al., 2014), with a gradient comparable with the longitudinal river one, the coast was shifted towards the northeast by roughly 30 km (Figs. 1, 12a; Lambeck et al., 2004; Pirazzoli, 1997), without inducing a significant reduction in the local base level. The small catchments that flow today into the sea were part of larger drainage systems affecting a broad low gradient coastal plain. The Cerrano and Calvano valleys were incorporated in this broad coastal plain and were partly filled by fluvial-colluvial deposits (now preserved in small remnants along strath terraces).

From the Late Pleistocene (LGM) to the Holocene, the landscape changes in the clayey hills catchments of the Apennines piedmont were largely controlled by a combination of sea-level rise and rapid climate warming. In addition, the Holocene marine transgression affected the coastal landscape that was uplifted of a few tens of metres with respect the previous sea-level highstand (Tyrrhenian, according to the general uplift rates of around 0.2–0.4 mm/yr) of the coastal Adriatic hilly area (D'Agostino et al., 2001; Centamore and Nisio, 2003; Pizzi, 2003; Cantalamessa and Di Celma, 2004; Cyr and Granger, 2008; Coltorti and Farabollini, 2008; Buccolini et al., 2010; Di Celma et al., 2015). The Holocene climate warming induced an intense linear erosion allowing the incision of the hydrographic network and the increase of slope steepness (biostasy conditions; Erhard, 1956; Benjamin et al., 2017). In the inland

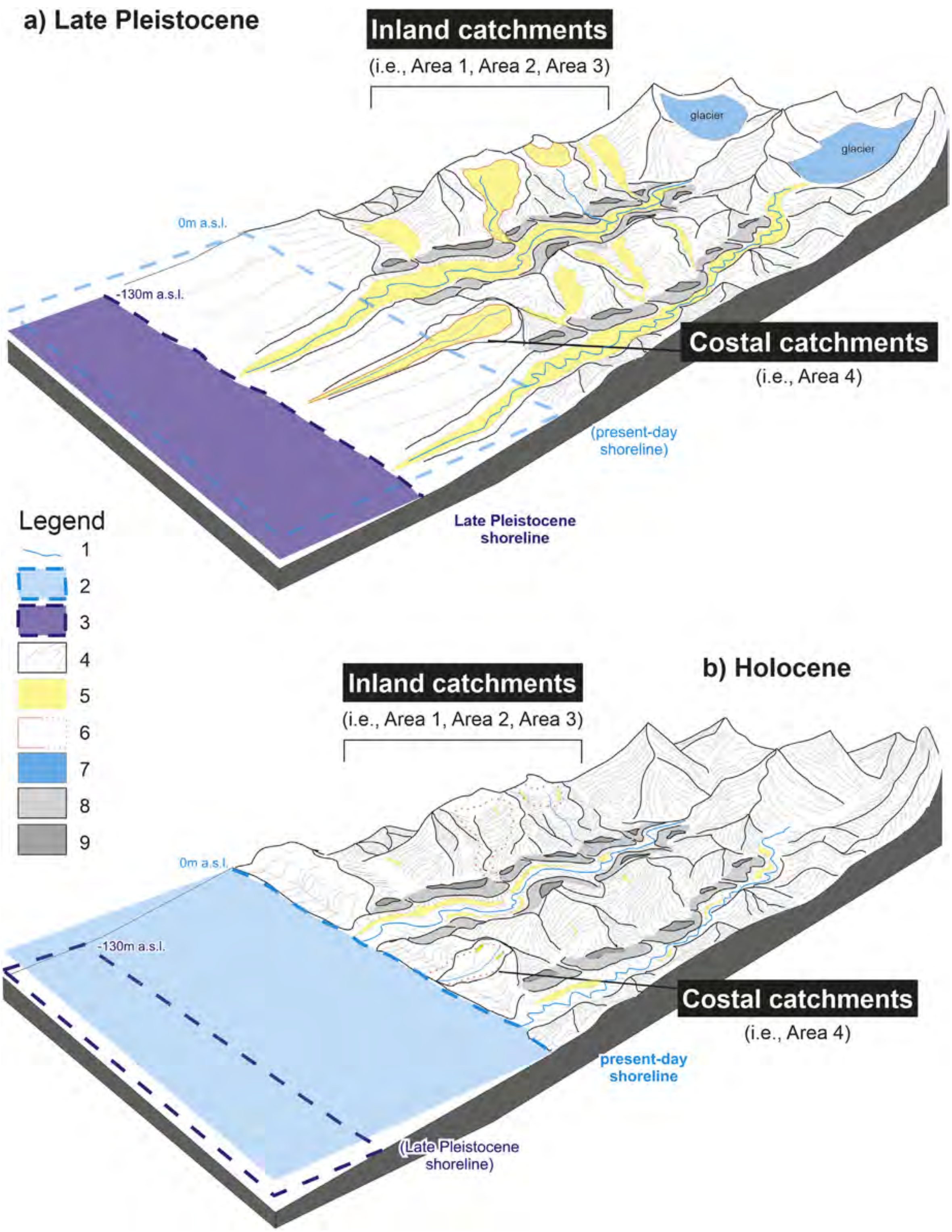


Fig. 12. Geomorphological block diagrams of the evolution of the inland and coastal small catchments. a) Late Pleistocene. b) Holocene. Legend: 1) main rivers and streams; 2) present sea-level and coastline; 3) Late Pleistocene (LGM) sea-level and coastline; 4) hills' morphology; 5) Late Pleistocene fluvial and slope deposits; 6) Late Pleistocene deposits' maximum extension; 7) Late Pleistocene glaciers; 8) end of Middle Pleistocene fluvial deposits; 9) Middle Pleistocene fluvial deposits.

areas, these conditions induced the incision of the Late Pleistocene major fluvial plains and the formation of fluvial terraces in the main valleys (Coltorti et al., 1991; Della Seta et al., 2008; D'Alessandro et al., 2008; Nesci et al., 2012; Miccadei et al., 2012, 2013). Within the small catchments, a progressive incision of the clayey landscape was induced, which was connected to landslide processes, mass wasting, and water erosion (Fig. 12b).

In coastal areas (i.e., the Atri area), the Holocene sea transgression (Parlagreco et al., 2011; Benjamin et al., 2017) was combined with tectonic uplift of a few tens of metres since the previous (Tyrrhenian) sea-level highstand (Lambeck et al., 2004; Antonioli et al., 2006; Ferranti et al., 2006). This combination led to the creation of an uplifted landscape with hanging valleys along the coast (Mizutani, 1996; Stewart and Morhange, 2009), and consequently, to a significant relief gradient and local base level change at the small catchment mouths that induced headwards erosion and incision processes in the coastal catchments (with erosion rates up to several mm/yr, Buccolini et al., 2010). This is consistent with observations in other northern Adriatic coastal catchments (Wegmann and Pazzaglia, 2009).

7. Conclusion

This study provides a synthesis of outcomes of geomorphological field investigations performed in several previous studies on inland and coastal small catchments in the hilly clayey landscapes of Central Italy and Northern Sicily combined with the definition of specific geomorphological markers (i.e. radiocarbon dating and geomorphological correlations among fluvial terraces and strath terraces). Specifically, the study focused on areas placed in different geodynamic sectors and affected by the late Quaternary uplift and climate-sea-level fluctuations. A comparison of the different study areas outlined similar evolutions and made it reasonable to define a common Late Pleistocene–Holocene evolution model of the small catchments in Apennine clayey hills of Central Italy and Sicily. This evolution can be summarised as follows:

a) End of Late Pleistocene (i.e. around 20,000 yrs. B.P., LGM, sea-level lowstand, rhexistasy conditions; Fig. 12a):
  - The major rivers were in a sedimentation phase induced by a large production of debris (cold-arid climate stage) and were forming broad fluvial plains (now preserved as the Late Pleistocene terraces).
  - On the slopes and along the valley sides, the small catchments were dominated by low gradient erosional surfaces with the deposition of thin fluvial-colluvial deposits and locally thick slope deposits. In agreement with Erhard (1956) and Pelletier (2003), the cold-arid climatic conditions and a low gradient morphology favoured areal erosion and sedimentation processes with the regularization of the landscape and the formation of broad minor valleys.

b) Holocene (i.e., from around 10,000 yrs. B.P. to present, last climate warming, sea transgression up to the present highstand, biostasy conditions; Fig. 12b):
  - The major rivers were in a general incision phase induced by reduced debris production (warm-humid climate stage) and were carving and terracing the Late Pleistocene fluvial plains.
  - In the small catchments, the Early Holocene climate warming and the combination of marine transgression and tectonic uplift (from the latest part of the Middle Pleistocene highstand to the Holocene one) have generally induced river incision and headwards erosion. Specifically, within the inland catchments, the incision of the fluvial plain of the main rivers induced the drop of the local base level in the small tributary catchments, with the dissection of fluvial and slope/colluvial deposits and the formation of the strath terraces. In the coastal catchments, the combination of uplift and sea-level fluctuations induced the local base level lowering, the formation of hanging valleys and their following incision. Late Pleistocene erosional surfaces and fluvial deposits were preserved as strath terraces defining the current geomorphological configuration.

In conclusion, the analysis and the comparison of the study areas reveals that the cyclic changes in river dynamics (i.e. incision, widening, sedimentation, incision and terracing), for the clayey small catchments, is mainly controlled by local base level changes, regardless its origin (e.g., incision of main rivers, combining of sea-level changes and uplift, etc), and climate and related landscape conditions (i.e., rhexistasy or biostasy conditions). The evidence of the cyclic changes is preserved on strath terraces, which are also connected to the erosion/sedimentation balance in the hillslope-valley system. Therefore, the lithological factor (i.e., clayey bedrock or soft rocks in general) is an essential requirement. The study also confirms that combination of tectonic uplift and sea level changes can either amplify or inhibit the river response in terms of erosion/incision. In the study cases, incision occurs during a transgression phase, due to the combination with tectonic uplift.

More in general, the outlined evolutionary mechanisms are not supposed to be exclusive of the clayey landscapes of the Apennines. They may represent a key to understanding the evolution of the coastal and inland, hilly small catchments throughout the western Mediterranean, where analogous lithologic/uplift/eustatic combinations exist. This is particularly true where the combined effect of tectonic uplift (albeit with different rates) and late Quaternary climate fluctuations have induced local base level changes, whether they are related to the incision of Late Pleistocene alluvial plains of the major rivers or to the uplift of the coastal areas.

Data availability

The data provided within the manuscript are available on request from the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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