Geografia Fisica e Dinamica Quaternaria
GFDQ 46 (2023), 125-134 DOI 10.4454/gfdq.v46.884

Vito AZZILONNA[1], Lucia CONTILLO[1*], Giuseppe CORRADO[1],
Giusy DIMOLA[1], Emanuele GIACCARI[1], Paolo GIANNANDREA[1],
Dario GIOIA[2], Marcello SCHIATTARELLA[1]

Multistadial physiographic evolution of the Bradano River catchment in Southern Italy

Abstract: Azzilonna V., Contillo L., Corrado G., Dimola G., Giaccari E., Giannandrea P., Gioia D., Schiattarella M., *Multistadial physiographic evolution of the Bradano River catchment in Southern Italy.* (IT ISSN 0391-9838, 2023). The Bradano River catchment, an about 3000 km^2 wide hydrographic basin located at the border between Basilicata and Apulia, in southern Italy, has been studied with the specific target to delineate its physiographic evolution, in terms of modification of its watershed perimeter and change in the fluvial network. To achieve this scope, land surfaces and other landforms have been mapped. The progressive enlargement of the catchment basin occurred in four evolutionary steps mainly due to fluvial processes triggered by base-level changes. The age of terraces and palaeosurfaces and the chronology and position of the ancient coastlines permitted a reliable reconstruction of the basin history, started in mid-Pleistocene times, with a major stage of basin development between that age and the late Pleistocene. Landslides scattered within the basin contributed as one of the main morphogenetic factor to shape the whole area in recent times (fourth Holocene stage) and are often genetically related to the fluvial processes. Mass movement data from multiple archives have been mapped in a novel inventory map. Based on these data, contour maps of landslide density have been designed in a GIS environment to define the zones of highest hazard in the study area.

Key words: Land surfaces, Catchment evolution, Landslide density, Bradano River fluvial network, Southern Italy.

Riassunto: Azzilonna V., Contillo L., Corrado G., Dimola G., Giaccari E., Giannandrea P., Gioia D., Schiattarella M., *Evoluzione fisiografica multistadiale del bacino imbrifero del Fiume Bradano in Italia meridionale.* (IT ISSN 0391-9838, 2023). Il bacino del Fiume Bradano copre un'area di poco più di 3000 km^2 posta a cavallo del confine tra Basilicata e Puglia. In questo lavoro viene delineata l'evoluzione fisiografica del bacino imbrifero in termini di modificazione del suo perimetro e cambiamento della geometria della rete fluviale. Per determinarne le tappe morfoevolutive, sono state accuratamente cartografate le superfici piane e le altre forme che, unitamente alle paleolinee di riva ottenute dagli orli interni dei terrazzi marini che aggettano sulla Piana ionico-metapontina, hanno permesso di stabilire le fasi della progressiva espansione fisiografica del bacino. Sono state in tal modo individuate quattro fasi evolutive legate ai processi fluviali innescati dalle variazioni del livello di base. L'età delle superfici terrazzate e le posizioni degli antichi complessi di foce hanno consentito un'adeguata ricostruzione della storia del bacino, iniziata nel Pleistocene medio, con un'importante fase di sviluppo tra il Pleistocene medio e il Pleistocene superiore. Nel corso dell'Olocene e nel vigente sistema morfoclimatico, i processi di erosione accelerata e franosità hanno efficacemente affiancato quelli fluviali nel modellamento dei versanti, come mostra l'elaborazione statistica dei dati relativi ai movimenti di massa.

Termini chiave: Superfici piane, Evoluzione planimetrica di bacino imbrifero, Densità di frana, Rete idrografica del Fiume Bradano, Italia meridionale.

INTRODUCTION

The planimetric geometry of fluvial networks is an important morphostructural indicator in tectonically active regions (Beneduce *et al.*, 2004). Also, the shape and modifications of the watershed trough the time of a catchment basin may represent basic elements of knowledge in the history of large territories with tectonic structures less evident than orogenic chain areas. Many foredeep zones, for example, are apparently poor of information regarding the Quaternary deformational behaviour but their hydrographic basins are important source of data on tectonic uplift and regional-scale geomorphic evolution. One of these cases is represented by the Bradano Trough, the foredeep of the southern Tyrrhenian-Apennine orogenic system. Such a foredeep is crossed by five major streams flowing toward the Ionian Sea. The northernmost fluvial basin is the

[1] *Dipartimento delle Culture Europee e del Mediterraneo (DiCEM), Università degli Studi della Basilicata, Matera.*
[2] *Consiglio Nazionale delle Ricerche, Istituto di Scienze del Patrimonio Culturale, (ISPC-CNR), Tito Scalo (Potenza).*
* *Corresponding author: Lucia Contillo (lucia.contillo@unibas.it)*

This work was granted by Next Generation UE - PNRR Tech4You Project funds assigned to Basilicata University (PP4.3.2 - Parks, forests, landforms, rural landscapes, and multifunctional agriculture, Scientific Coordinator: Professor Marcello Schiattarella) - Technologies for climate change adaptation and quality of life improvement", field of intervention "5. Climate, Energy and Sustainable Mobility", Code ECS00000009 – CUP C43C22000400006

Bradano River valley (whose name is used to denominate the entire first-order physiographic unit of the foredeep as well), included for the most part in the foreland domain. Only its westernmost sector falls in the orogenic belt, constituting the thrust front of the chain. We choose this basin for its relative homogeneity both from lithological and morphological viewpoints, in order to delineate the evolutionary steps of the catchment in terms of modification of its watershed perimeter and change in the fluvial network. This allowed reconstructing the physiographic evolution of the basin in a precise chronological framework.

The Bradano Trough was largely investigated from a geological (mainly stratigraphic) point of view and, in a subordinate amount, included in regional/geodynamic studies (Balduzzi *et al.*, 1982; Pieri *et al.*, 1997; Tropeano *et al.*, 2002; Patacca and Scandone, 2007; Corrado *et al.*, 2017, among others). Also geomorphological works were performed in the foredeep area (Ricchetti, 1967; Hearty, Dai Pra, 1992; Zander *et al.*, 2006; Santoro *et al.*, 2013; Tropeano *et al.*, 2013; De Santis *et al.*, 2020), but not specifically on the fluvial nets which cut that major physiographic unit (Boenzi *et al.*, 2008; Giannandrea, 2009; Corrado *et al.*, 2017; de Musso *et al.*, 2020). The Quaternary landscape evolution was driven by a more or less continuous tectonic uplift that led, furthermore, to the formation of a marine terrace staircase (Caputo *et al.*, 2010; Tropeano *et al.*, 2013; Di Leo *et al.*, 2018; Gioia *et al.*, 2018; Gioia *et al.*, 2020; Corrado *et al.*, 2022).

The aim of our work is to better delineate the physiographic evolution of the Bradano River basin, in terms of modification of its perimeter and change in the fluvial network geometry because of the consequences of base-level changes. Relics of flat erosional land surfaces are spread at the top of the hills and mountains or at mid-slope positions in the whole study area. Also marine and fluvial terraces are largely scattered in the entire basin. Due to their arrangement and age, all these morphological flat surfaces represent a key to reconstruct ancient configurations of the Bradano River valley. This catchment is located for a large part in the eastern portion of the Basilicata, and for a smaller portion within the Apulian territory. It borders the basin of the Ofanto River to the north-west (which has some palaeogeographical relationships with the Bradano basin), the Basento River basin to the south (which shares the southern top land surfaces of the Bradano basin), and the Murgia Plateau to the north-east (on which the highest palaeosurface is moulded).

GENERAL OUTLINES OF THE STUDY AREA

The NW-SE-trending Bradano foredeep basin is located between the Apennine chain and the Murgia carbonate platform of the Apulian foreland, in southern Italy (fig. 1). The eastern Adriatic-verging thrust front of the chain, made of Tertiary terrigenous successions (Patacca and Scandone, 2007, and references therein) characterizes the westernmost portion of the Bradano catchment. Part of its orographic left (i.e., the north-eastern flank) is moulded in the Mesozoic limestone of the Apulian carbonate platform. The rest of the basin falls in the Bradano foredeep domain (fig. 1).

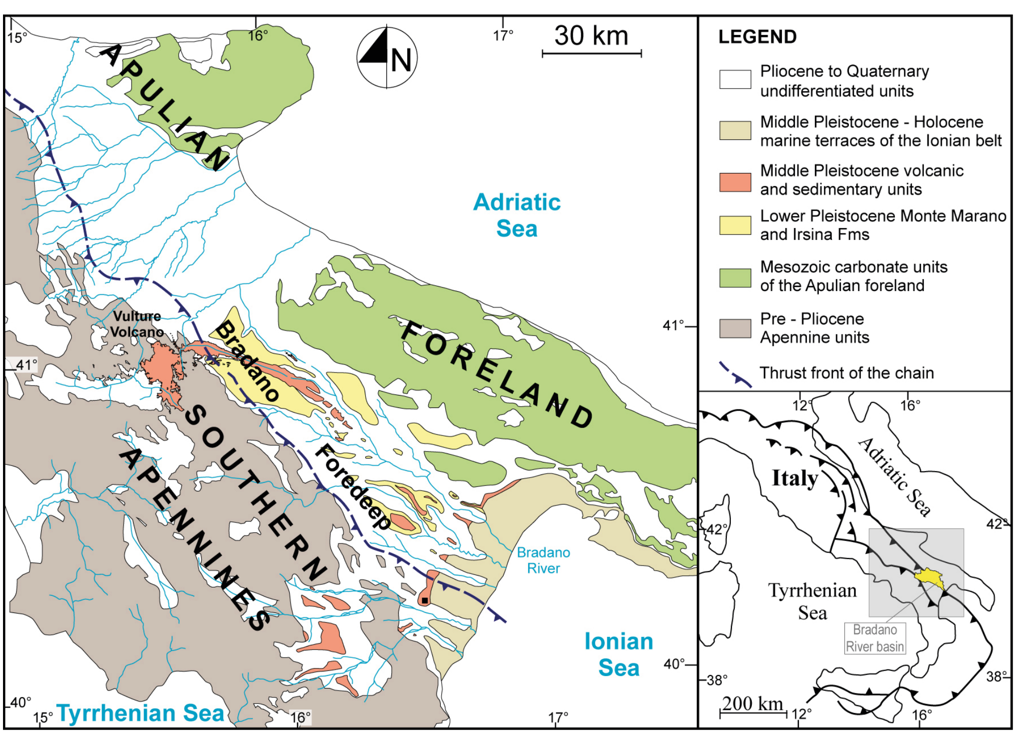

Figure 1 - Tectonic sketch map of Campania-Lucania Apennine and its foreland (modified after Corrado *et al.*, 2017), with location of the Bradano River basin in southern Italy.

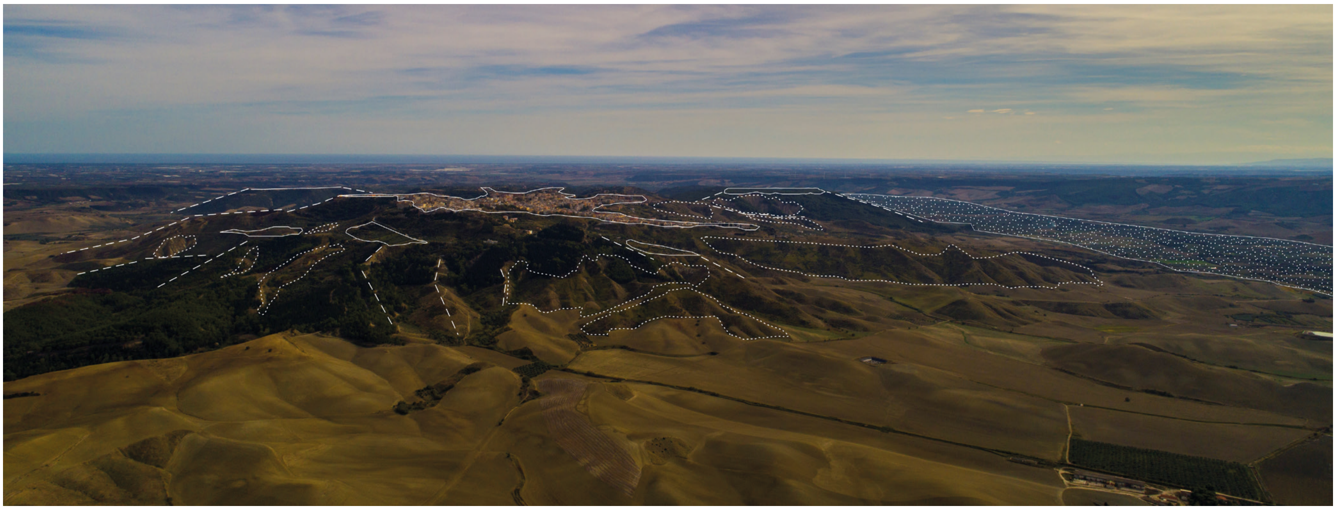

Figure 2 - The Montescaglioso village hill (viewed from the north), a mesa in the hydraulic left of the lower valley of the Bradano River. The lower Pleistocene clayey formation of the Argille subappennine constitutes the most part of the slopes of that morphostructure, whereas a calcarenite caprock forms the upper part of the hill. Line-drawing legend: the continuous line indicates the top land surface; dashed lines trace the hillslope ridges; dotted lines indicate slope areas affected by accelerated erosion phenomena; the dotted area indicates the flat-bottomed lower valley of the Bradano River.

The foredeep basin is filled by several km-thick Pliocene-Pleistocene deposits (Balduzzi *et al.*, 1982; Tropeano *et al.*, 2002). The upper Pliocene-lower Pleistocene outcropping succession (Ricchetti, 1967) is made of several hundred metres thick clayey marine deposits (*Argille subappennine* Fm) passing toward the top to regressive sands (Sabbie di Monte Marano) and conglomerate (Conglomerati di Irsina).

The study area is largely characterized by mesa-like landforms, moulded in a clayey-sandy succession overlain by conglomerates or locally by calcarenite forming the caprock of the mesas (fig. 2). Beneduce *et al.* (2004) assumed that the fluvial net cutting in the Matera horst and its surroundings, not far from the study area, started to be entrenched during mid-Pleistocene times. This assumption comes from the analysis of a 50 cm-thick bed of reworked pyroclastic rocks in the upper part of a clastic deposit associated to a fluvial terrace outcropping about 10 km southwest of Matera town. The volcanic minerals in the clastic component of this layer include sanidine, clinopyroxene and phlogopite, suggesting that the most suitable source supplying the volcanic mineral assemblage was the lower part of the Mount Vulture volcanic succession (Schiattarella *et al.*, 2005; Giannandrea *et al.*, 2006). Relevant outcrops of the mid-Pleistocene products of Mt. Vulture have been recognized in the Venosa lacustrine-alluvial basin (Giannandrea, 2009), adjacent to the volcanic edifice and partly included in the study area, and in the southernmost sector of the Bradano foredeep (Corrado *et al.*, 2017).

Toward the Ionian coast, the marine clays of the foredeep (*Argille subappennine* Fm) are unconformably overlaid by a middle-upper Pleistocene regressive, generally coarsening upward, succession of marine silt, sand, and conglomerate. This succession forms a staircase of marine terraces corresponding to discrete depositional coastal wedges. Since middle Pleistocene, in fact, the interplay between tectonic uplift and eustatic sea-level variations promoted the development of several orders of marine terraces, which are arranged in a staircase geometry with a systematically decrease of altitude from the oldest to the youngest (Caputo *et al.*, 2010; Corrado *et al.*, 2022). The top of the youngest and the lowest coastal wedge is the present-day Metaponto coastal plain (Tropeano *et al.*, 2013; Corrado *et al.*, 2022). Continental deposits belong to alluvial environments, either located along the channels of the main rivers or on wide floodplains, whereas transitional deposits belong to delta and beach environments constituting the present-day shoreline.

From a geomorphological point of view, the study area is characterized by landforms of the front of the chain (NW-SE elongated ridges in soft rocks), of the Bradano Trough (mesas with slopes largely affected by badlands), and of the Apulian foreland (flat-topped carbonate morphostructures, locally featured by deep gorges).

METHODS

Land surface analysis

In order to reconstruct the physiographic evolution of the investigated hydrographic basin and for the definition of the evolutionary steps that have determined its current shape, field surveys and the use of high-resolution Digital Elevation Models (5 m - https://rsdi.regione.basilicata.it/) allowed identifying the flat surfaces, then classified by elevation analysis carried out in GIS environment. The cartographic representation of the geomorphological elements was carried out according to the guidelines of the *Quaderno Serie III Volume 13* of the *Servizio Geologico Nazionale* for the achievement of the Geomorphological Map of Italy at 1:50,000 scale. The geomorphological map of the catchment basin of the Bradano River illustrates the fluvial landforms of major floodplains and the flat surfaces of various origin (fig. 3).

Landslide analysis

For a more complete understanding of the morphological history of the Bradano River basin, in addition to fluvial processes, the gravitational-type phenomena affecting the area in more recent times have been investigated as well. Mass movements have in fact heavily affected the study area in the youngest evolutionary stage. Landslides made available by ISPRA - IFFI Project (*Inventario dei Fenomeni Franosi in Italia*) – which provides a detailed overview of the distribution of landslide phenomena in Italy, and by PAI (*Piani di Assetto Idrogeologico*), managed by the Southern Apennine Hydrographic District, have been collected, validated, and statistically evaluated. The datasets were managed and processed in a GIS environment and georeferenced in the WGS 84 UTM Zone 33N coordinate system (EPSG: 32633).

Landform mapping and data processing

The different orders of sub-horizontal surfaces of fluvial genesis at medium-low elevations (fill-and-strath terrace types), and those identified at higher elevations (i.e., paleosurfaces related to older erosion base levels), have been used for the reconstruction of the morphoevolutionary stages of the Bradano River catchment. We referred to different ages of marine terraces for the definition of the outlet points of the hypothesized stages, using the inner edges of the terraces as ancient coastlines (data from Gioia *et al.*, 2016, 2020). Structural surfaces (e.g. depositional tops of the regressive cycle of the Bradano foredeep) and landslide terraces (i.e., sub-horizontal or gently sloping surfaces present within larger landslide bodies of significant size) have also been mapped.

Data from scientific literature helped us to better constrain the chronology of the evolutionary stages (Beneduce *et al.*, 2004; Caputo *et al.*, 2010; Tropeano *et al.*, 2013; Petrosino *et al.*, 2015; Corrado *et al.*, 2017).

In the Bradano River basin 13,299 landslides have been mapped, of which 555 are managed by the IFFI project and 12,744 proposed by PAI, re-catalogued and managed according to the type of movement. Since the mapping of landslides during the works of PAI was strongly concentrated around the inhabited areas, the contouring for map analysis may produce a clustering effect in the surroundings of towns and villages (fig. 4). On the basis of this information, the predominant movements were grouped into the following types for the "Kernel Density" estimate: roto-translational landslides, earthflows, and shallow landslides (as discussed in the next section). In particular, the Kernel density GIS computation tool allowed us to extract an area output of landslide density, exploiting an algorithm that calculates distances using the geodetic method in the case of punctual input features. Therefore, it was necessary to calculate the centroids for each polygonal layer. The Kernel density methodology calculates density of features using a Gaussian function in the circular portion at each output cell. The surface value has a greater value at the point until it reaches zero when the distance to the point is equivalent to the search distance. The density for each cell is calculated by adding the values of all kernel surfaces at the point where they overlap the centre of the output cell. The Kernel function is based on the Quartico Kernel function described in Silverman (1986, cf. equation 4.5). The search radius, if not specified, is predefined by applying an algorithm to the data based on the extent of the data and the density of the points; the cell size, if not provided, is calculated according to the formulas described in Hengl (2006). The unit area was automatically calculated by the software by setting "square kilometres" for the output area density units, in order to generate square kilometres for the point elements. The processing was repeated for the input features of the different types of movements and on the total amount of landslides found, giving back a density map with the Kernel density values per unit area for each cell. Finally, for greater graphical output, a filter was applied excluding values between 0 and 1.

Several other approaches have been proposed in the specialist literature for the assessment of landslide hazard and risk. Scientific works have focused on the assessment of landslide hazard in rather limited areas and less interest has been devoted to large portions of territory. Further, there is still no agreement either on methods or on the purposes of how to produce hazard maps. Hence the need to identify the different factors that contribute to the elaboration of a GIS that replaces the classical cartographic representation of the different hazard scales to be implemented over the fairly wide area of the Bradano River basin. In this area, all the homogeneous features of the cells of minor extension have been identified to contribute to the future construction of a platform for hazard estimation, also based on multivariate statistical techniques (Guzzetti *et al.*, 1999). Yet, the hazard assessment of the Bradano River basin pilot project requires detailed and, above all, uniformly distributed information on the temporal recurrence of landslide phenomena and/or their causes (rainfalls, earthquakes, anthropic interventions) not considered in this work.

RESULTS AND DISCUSSION

Structural landforms dominate the physical landscape of the area of the Bradano River basin. Monocline structures in the western sector (coinciding with the thrust front of the chain), tabular relief characterized by horizontal sedimentary layers and flat top surfaces, sometimes modelled by selective erosional processes that determine a mesa-type style (in the most part of the basin included in the foredeep), and deep fluvial incisions with sub-vertical flanks (gorges) in the carbonates of the foreland (Murgia), with flat surfaces affected by fluvio-karst processes at the top of the morphostructural highs, are largely observed (fig. 3).

Fast and intense erosional processes affected the different geological formations outcropping in the basin. Runoff surfaces (i.e., slope surfaces in which vegetation cover is not significantly present and on which un-channelled water operates) are widespread. Gullies, accelerated erosion channels and/or badlands are diffused where the clay-sandy lithology and limited annual rainfall promote such processes (i.e., in a wide part of the study area where the *Argille subappennine* Fm crops out).

The main watercourse is mostly meandering: in its central section, mobile channels are present, with ephemeral 'islands' of fluvial coarse sediment (longitudinal bars) due to the low gradient of the watercourse and poorly competent current. The bottom of the main valleys is occupied by flat floodplains (as in the case of Bilioso, Tolve, and Basentello streams, besides the Bradano River) articulated in active channels, floodable areas and low-elevation terraced lateral belts, which was once reached by the alluvial deposition of fine materials. On the sides of the floodplains, directly overhanging the valley floor, there are also alluvial fans, generated by the transport and deposition of material from the tributaries, mainly in the central section of the catchment.

Flat land surfaces can be classified as follows (fig. 3): i) sub-horizontal surfaces at medium-low elevations by fluvial processes (fill-and-strath terrace type), ii) those identified at higher elevations as erosional paleosurfaces or structural surfaces (e.g. depositional tops of the regressive cycle of the Bradano foredeep), iii) marine terraces in the south-eastern downstream area; iv) landslide terraces, also sub-horizontal or gently dipping counterslope surfaces within larger landslide bodies. Such features have been used in this work to determine the ancient base levels due to the interplay between tectonics and glacio-eustatic sea-level variations, and to estimate the amount of area of the Bradano palaeocatchments. Previous works set the age of the genesis and following embankment of the fluvial palaeo-networks in the foredeep area at mid-Pleistocene times (Beneduce *et al.*, 2004; Corrado *et al.*, 2017).

Since the highest marine terrace of the study area was referred to MIS 15 (i.e., 570-590 ka, Gioia *et al.*, 2020, and references therein) and the land surfaces at the top of the regressive succession of the foredeep (Sabato *et al.*, 2004) have to be younger than 730 ka (age of the top of the Irsina conglomerate and/or age of suture and weathering of the uppermost deposits, Corrado *et al.*, 2017), one can deduce an age roughly comprised between 600 and 700 ka for the erosional palaeosurfaces surveyed within the basin. As a matter of fact, the marine terrace staircase is morphologically inset in the erosional palaeosurfaces, in turn inset in the foredeep depositional top. The fluvial terraces are organized in two main orders along the major stream, morphologically inset in both the erosional palaeosurfaces and the upper marine terraces. For such reasons, land surface correlations between fluvial and marine terraces allowed us to reconstruct the main morphological phases of study area since the middle Pleistocene. Four morpho-evolutionary stages have been identified (fig. 5).

The base level during the first stage is slightly older than the palaeocoastline that corresponds to the inner edge of the oldest marine terrace (about 600 ka, age from the geomorphological map in Gioia *et al.*, 2020). Therefore this phase can be attributed to an age of 700-600 ka, in coincidence of the main ignimbrite eruption of Mount Vulture Volcano. In this stage, the palaeo-Fiumara di Venosa still drained to the Bradano River basin (fig. 6).

In the second stage, the basin area amounted to about 1135 km^2 (37.6% of the current basin area and about 30% smaller than the first-stage palaeobasin), being loss the north-western portion of the palaeocatchment due to the piracy phenomenon exerted by the Ofanto River system (fig. 6). In other words, starting from about 500 ka (Giannandrea *et al.*, 2006; Giannandrea, 2009), the Venosa palaeostream was integrated into a fluvial system located to the north-west of the studied area and flowing toward the Adriatic Sea. Since minor watercourses, over time, have cut and eroded the river terraces, many surfaces are currently fragmented. Many of these relics form a fan-shaped pattern in the mid-upper portion of the present-day basin which seems to emulate the upper part of the palaeowatershed. The higher palaeosurfaces and the palaeoshoreline at about 300 ka (after Gioia *et al.*, 2020) allowed bordering the whole second-stage ancient catchment.

The third stage of this reconstruction occurred with the base level at 125 ka (Late Pleistocene, Tyrrhenian Stage). The erosion base level related to this stage corresponds to the palaeocoastline coinciding with the inner edge of the MIS 5.5 marine terrace (data from the geomorphological map in Gioia *et al.*, 2020). During this phase the basin area was about 2320 km^2 (76.8% of the current basin area) and conquered most part of the present-day drainage area (more than 40% in this time-span). The basin expands northeast to the Apulian foreland including the Gravina di Matera stream and gorge system (up to the Altamura plateau). In the south-western portion, the boundary of the catchment area coincides with the current water parting.

In the present-day stage, the Bradano basin has reached an extension of 3018.78 km^2. Such a physiographic history suggests that the regressive fluvial erosion with progressive fluvial piracy phenomena – at least starting from the second stage of the above illustrated model – has represented the main modality of rock dismantling and drainage evolution. In the first stage, instead, the complex interplay among volcanic activity, tectonics, and erosion dominates the evolutionary scenario of the fluvial basin, leading to the reduction of the upstream area.

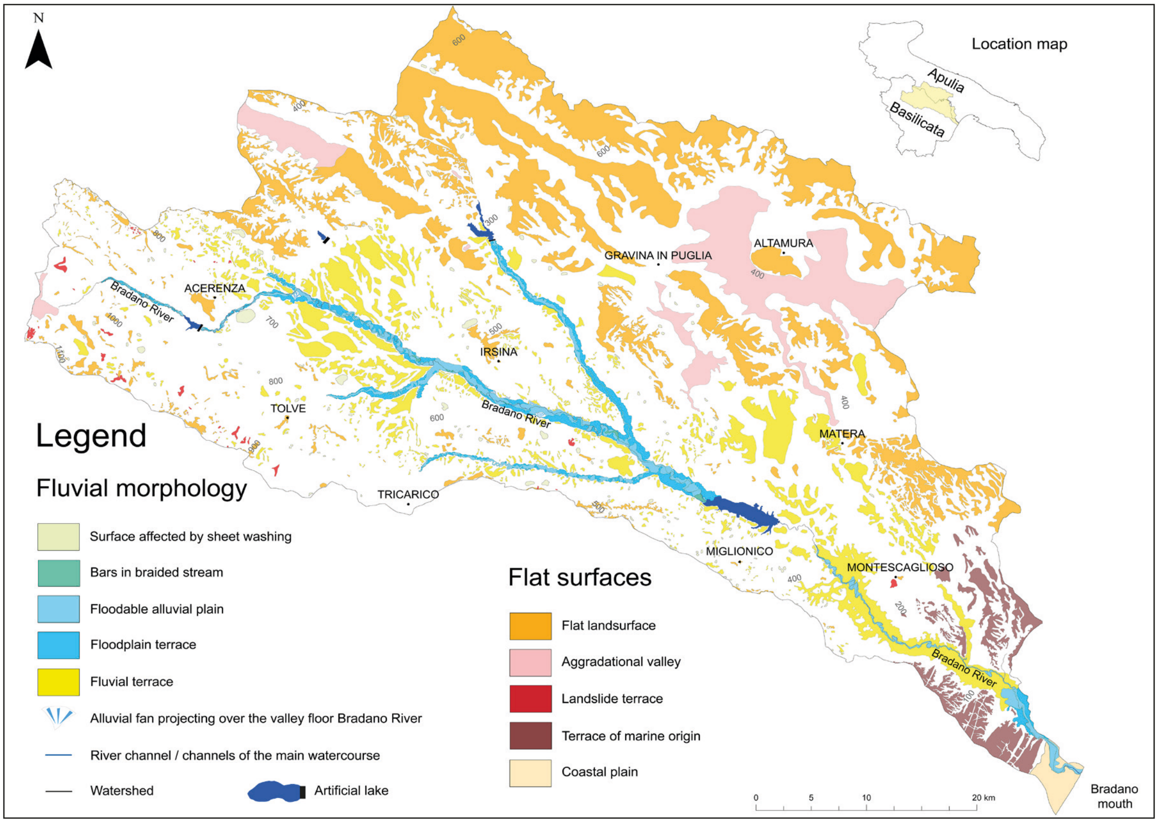

Figure 3 - Arrangement of the land surfaces of the Bradano River catchment and morphological subdivision of the main floodplains.

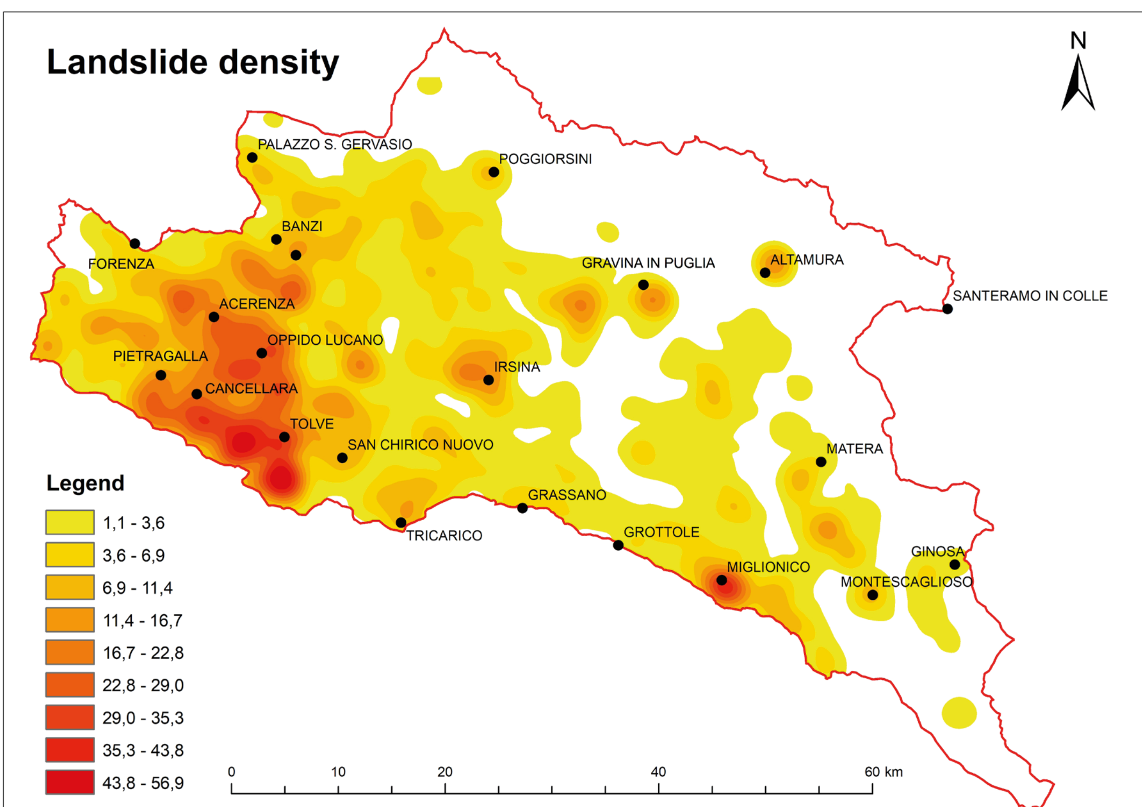

Figure 4 - Landslide density map of the study area. All mass movements from archives are reported.

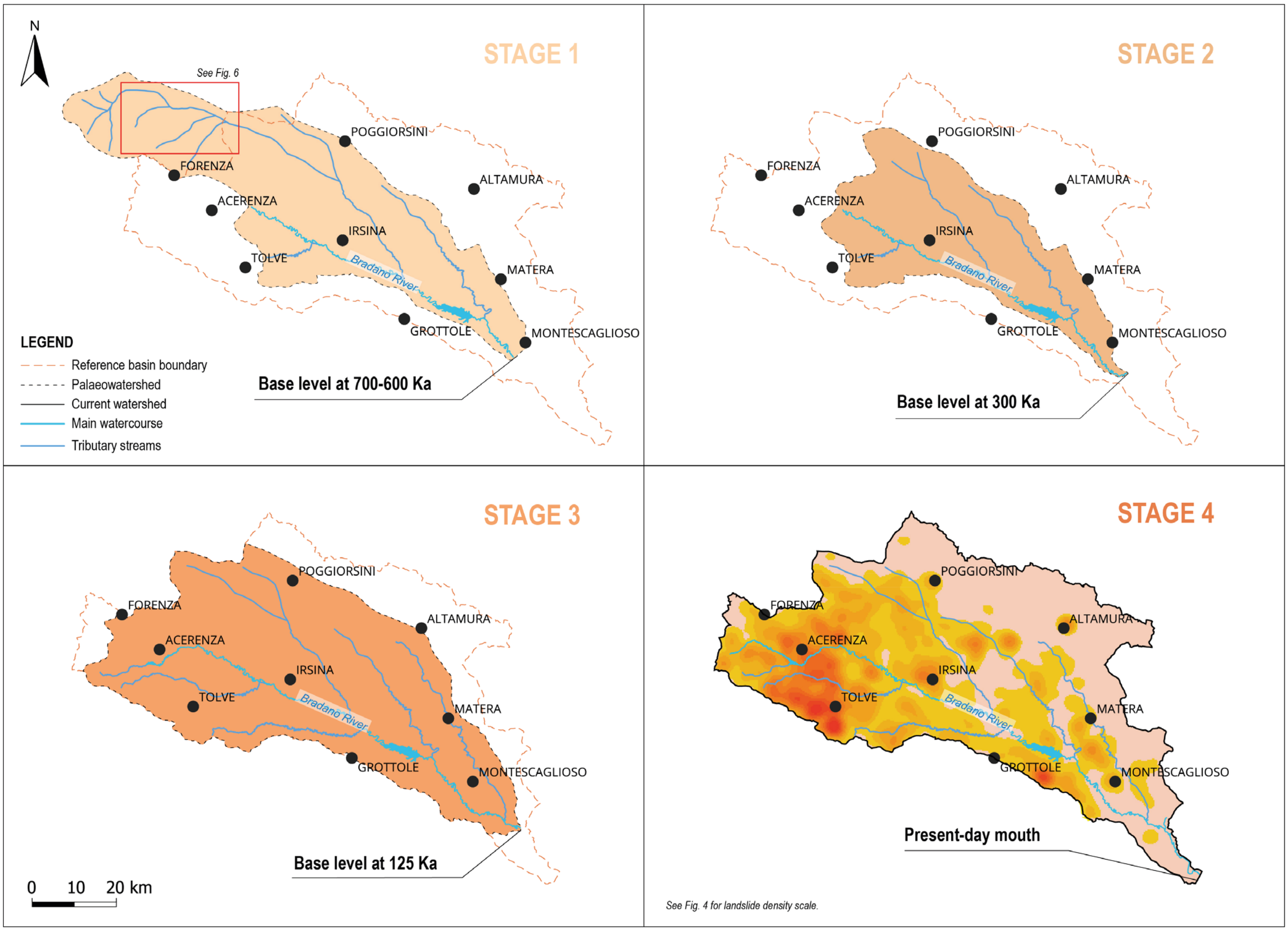

Figure 5 - Physiographic multistage evolution of the Bradano basin (see text for explanation). Note that the hydrographic pattern reported in the sketch map is just a geographic reference element and the Kernel density arrangement of landslides in the stage 4 frame is the same of figure 4.

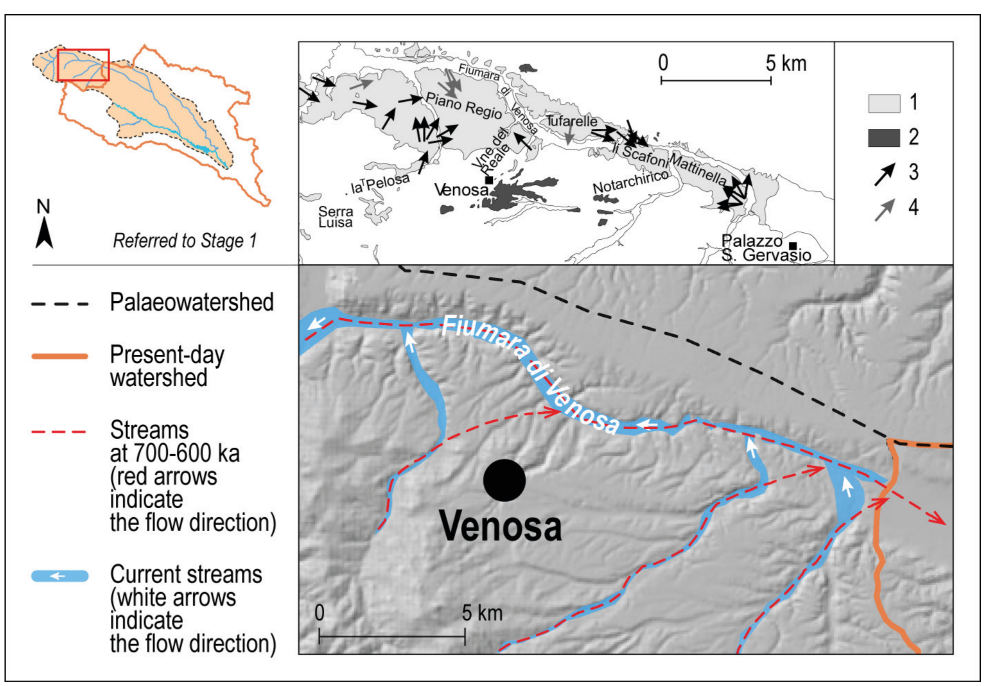

Figure 6 - Morphological and sedimentological markers of reverse drainage phenomena affecting the Fiumara di Venosa stream and its tributaries (palaeocurrent data after Giannandrea, 2009). Legend: 1. Venosa basin units; 2. Volcanic and epiclastic deposits of Serra Luisa hill; 3. Barile synthem palaeocurrent markers (cross lamination and pebble embricates); 4. Foggianello Synthem palaeocurrent markers (cross lamination and pebble embricates).

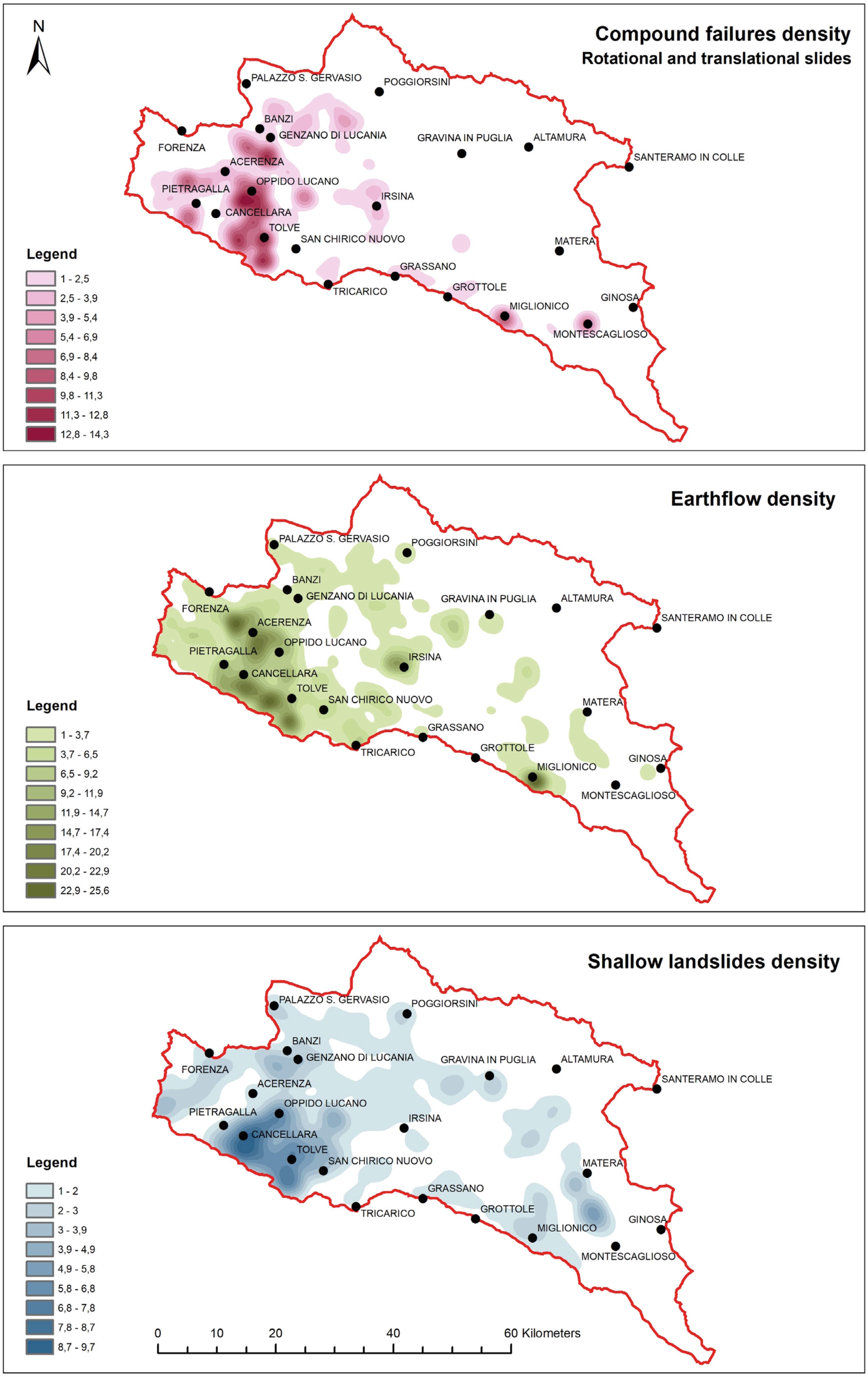

Figure 7 - Landslide density maps of the study area for single types of mass movements.

Figure 8 - The San Giuliano artificial lake along the lower valley of the Bradano River. In the foreground, a tributary valley shows its left slope affected by badlands. In the background, the flat-topped hill of Montescaglioso is well visible.

The fourth stage of our reconstruction roughly corresponds to the Holocene, and it is associated with the post-glacial climate. During this phase gravitational-type processes joined the fluvial linear erosion as an additional evolutionary element of the physiographic framework. As a matter of fact, the study area is characterized by a large presence of landslide bodies. The analysis of their spatial distribution based on the "Kernel density" estimation (figs 4 and 5) highlighted a higher instability in the upstream area of the basin, underlining a greater structural and lithological control, besides the influence of a higher value of rainfalls. In addition, the Kernel density calculation allowed us to recognize the distribution of predominant types of mass movements (fig. 7). We noticed that earthflow and shallow landslides are the most widespread gravitational movement types, but compound and roto-traslational landslides are concentrated in the upstream zone of the catchment basin. In more recent times (historical period), fluvial erosion and deposition, mass movements, and accelerated erosion phenomena (badlands) compete in shaping the slopes of the Bradano River basin (fig. 8), by a constant interplay of different processes. Sheet washing is mainly present in the central-eastern zone of the study area (i.e., in the foredeep slopes), together with ephemeral channeled erosions and gullies. V-shaped and flat-bottomed minor valleys are widespread within the catchment basin. Sometimes, the flat-bottomed valleys present incised infill and are coupled to little alluvial fans or landslides at the foot of the related slopes.

FINAL REMARKS

The age of the terraced surfaces and summit flat palaeosurfaces of the Bradano River catchment, an about 3020 km^2 large hydrographic basin of southern Italy, and chronology and position of the ancient coastlines (i.e., the location of the basin palaeomouths) have been used to reconstruct the main evolutionary steps of the study area, mainly from a physiographic/planimetric viewpoint. Such an approach may offer some useful constrains in reconstructing basin palaeomorphological configurations, producing a faster and more realistic view of past shapes than procedures based on sediment unroofing methods or erosion rate estimations, and furnishing an additional tool to the stream profile analysis.

The history of the basin started in the early middle Pleistocene, whereas a major stage of basin development occurred between the middle and the late Pleistocene. In this work, the progressive (multistadial) enlargement of the catchment basin has been codified into four steps mainly due to fluvial processes triggered by base-level changes. It is possible to affirm that the modifications of the basin perimeter and changes in the fluvial network are framed in a scenario of retrogressive erosion, with a progressive enlargement toward west of the upstream portion and related fluvial piracy phenomena. Such dynamics was preceded by the loss of the branch of the Venosa stream (Fiumara di Venosa), captured by the Ofanto River drainage system after the first stage of evolution.

During the Holocene, mass movements and accelerated linear erosion took place in the area, joining the fluvial erosion as main mechanisms of morphological evolution of slopes. From this point of view, the area of the highest landslide hazard coincides with the westernmost portion of the fluvial catchment, where the allochthonous units of the Apennine chain crop out, as clearly shown by contour maps of landslide density constructed in a GIS environment. This may be due to the greater tectonic mobility of that sector, coupled to higher amounts of rainfalls.

REFERENCES

AA.VV., 2021. *Aggiornamento ed integrazioni delle linee guida della Carta Geomorfologica d'Italia alla scala 1:50.000 e banca dati geomorfologica*. Progetto CARG: modifiche ed integrazioni al Quaderno n. 4/1994. Quaderni del Serv. Geol. d'It., Serie III, 13 (1), ver 2.0, A cura di Campobasso C., Carton A., Chelli A., D'Orefice M., Dramis F., Graciotti R., Guida D., Pambianchi G., Peduto F., Pellegrini L. ISPRA, Roma, 95 pp.

Balduzzi A., Casnedi R., Crescenti U., Mostardini F., Tonna M., 1982. *Il Plio-Pleistocene del sottosuolo del Bacino Lucano (Avanfossa Appennini nica)*. Geologica Romana, 21, 89-111.

Beneduce P., Festa V., Francioso R., Schiattarella M., Tropeano M, 2004. *Conflicting drainage patterns in the Matera Horst Area, Southern Italy*. Physics and Chemistry of the Earth, 29, 717-724.

Boenzi F., Caldara M., Capolongo D., Dellino P., Piccarreta M., Simone O., 2008*. Late Pleistocene-Holocene landscape evolution in fossa Bradanica, Basilicata (Southern Italy)*. Geomorphology, 102, 297-306.

Caputo R., Bianca M., D'Onofrio R., 2010. *Ionian marine terraces of Southern Italy: Insights into the Quaternary tectonic evolution of the area*. Tectonics, 29, TC4005 (1-24).

Corrado G., Aiello G., Barra D., Di Leo P., Gioia D., Minervino Amodio A., Parisi R., Schiattarella M., 2022. *Late Quaternary evolution of the Metaponto coastal plain, southern Italy, inferred from geomorphological and borehole data.* Quaternary International, 638-639, 84-110.

Corrado G., Di Leo P., Giannandrea P., Schiattarella M., 2017. *Constraints on the dispersal of Mt. Vulture pyroclastic products: implications to mid-Pleistocene climate conditions in the foredeep domain of Southern Italy.* Géomorphologie: Relief, Processus, Environnement, 23 (2), 171-182.

De Musso N.M., Capolongo D., Caldara M., Surian N., Pennetta L., 2020. *Channel Changes and Controlling Factors over the Past 150 Years in the Basento River (Southern Italy).* Water, 12, 307 (1-22).

De Santis V., Caldara M., Torres T., Ortiz J.E., Sánchez-Palencia Y., 2020. *The role of beach ridges, spits, or barriers in understanding marine terraces processes on loose or semiconsolidated substrates: Insights from the givoni of the Gulf of Taranto (southern Italy).* Geological Journal, 55 (4), 2951-2975.

Di Leo P., Bavusi M., Corrado G., Danese M., Giammatteo T., Gioia D., Schiattarella M., 2018. *Ancient settlement dynamics and predictive archaeological models for the Metapontum coastal area in Basilicata, southern Italy: from geomorphological survey to spatial analysis*. Journal of Coastal Conservation, 22, 865-877.

Giannandrea P., 2009. *Evoluzione sedimentaria della successione alluvionale e lacustre quaternaria del Bacino di Venosa (Italia meridionale).* Il Quaternario, 22 (2), 269-290.

Giannandrea P., La Volpe L., Principe C., Schiattarella M., 2006. *Unità stratigrafiche a limiti inconformi e storia evolutiva del vulcano medio-pleistocenico di Monte Vulture (Appennino meridionale, Italia).* Bollettino della Società Geologica Italiana, 125, 67-92.

Gioia D., Bavusi M., Di Leo P., Giammatteo T., Schiattarella M., 2016. *A geoarchaeological study of the Metaponto coastal belt, Southern Italy, based on geomorphological mapping and GIS-supported classification of landforms*. Geografia Fisica e Dinamica Quaternaria, 39 (2), 137-148.

Gioia D., Bavusi M., Di Leo P., Giammatteo T., Schiattarella M., 2020. *Geoarchaeology and geomorphology of the Metaponto area, Ionian coastal belt, Italy*. Journal of Maps, 16 (2), 117-125 (Map available online at https://doi.org/10.1080/17445647.2019.1701575).

Gioia D., Schiattarella M., Giano S.I, 2018. *Right-angle pattern of minor fluvial networks from the Ionian terraced belt, southern Italy: passive structural control or foreland bending?* Geosciences, 8, 331-350.

Guzzetti F., Carrara A., Cardinali M., Reichenbach P., 1999. *Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy*. Geomorphology, 31, 181-216.

Hearty P.J., Dai Pra G., 1992. *The age and stratigraphy of Middle Pleistocene and younger deposits along the Gulf of Taranto (southeast Italy).* Journal of Coastal Research, 8, 882-905.

Hengl T., 2006. *Finding the right pixel size*. Computers Geosciences, 32 (9), 1283-1298.

Patacca E., Scandone P., 2007. *Geology of the Southern Apennines*. Bollettino della Società Geologica Italiana, Special Issue, 7, 75-119.

Petrosino P., Jicha B.R., Mazzeo F.C., Ciaranfi N., Girone A., Maiorano P., Marino M., 2015. *The Montalbano Jonico marine succession: an archive for distal tephra layers at the Early-Middle Pleistocene boundary in Southern Italy*. Quaternary International, 383, 89-103.

Piccarreta G., Ricchetti G, 1970. *I depositi del bacino fluvio-lacustre della Fiumara di Venosa-Matinelle e del Torrente Basentello. Studio geologico-petrografico*. Memorie della Società Geologica Italiana, 9, 121-134.

Pieri P., Vitale G., Beneduce P., Doglioni C., Gallicchio S., Giano S.I., Loizzo R., Moretti M., Prosser G., Sabato L., Schiattarella M., Tramutoli M., Tropeano M., 1997. *Tettonica quaternaria nell'area bradanico-ionica.* Il Quaternario, 10, 535-542.

Ricchetti G., 1967. *Lineamenti geologici e morfologici della media valle del Fiume Bradano*. Bollettino della Società Geologica Italiana, 49, 421-622.

Sabato L., Tropeano M., Pieri P., 2004. *Problemi di cartografia geologica relativa ai depositi quaternari del F° 471 "Irsina". Il Conglomerato di Irsina: mito o realtà?* Il Quaternario, Italian Journal of Quaternary Sciences, 17 (2/1), 391-404.

Santoro E., Ferranti L., Burrato P., Mazzella M.E., Monaco C., 2013. *Deformed Pleistocene marine terraces along the Ionian Sea margin of southern Italy: Unveiling blind fault-related folds contribution to coastal uplift*. Tectonics, 32, 737-762.

Schiattarella M., Beneduce P., Di Leo P., Giano S.I., Giannandrea P., Principe C., 2005. *Assetto strutturale ed evoluzione morfotettonica quaternaria del vulcano del Monte Vulture (Appennino Lucano)*. Bollettino della Società Geologica Italiana, 124, 543-562.

Silverman B.W., 1986. *Density Estimation for Statistics and Data Analysis*. New York, Chapman and Hall.

Tropeano M., Cilumbriello A., Sabato L., Gallicchio S., Grippa A., Longhitano S.G., Bianca M., Gallipoli M.R., Mucciarelli M., Spilotro G., 2013. *Surface and subsurface of the Metaponto Coastal Plain (Gulf of Taranto-southern Italy): Present-day vs LGM-landscape*. Geomorphology, 203, 115-131.

Tropeano M., Sabato L., Pieri P., 2002. *Filling and cannibalization of a foredeep: Bradanic Trough, Southern Italy*. Geological Society, London, Special Publications, 191, 5579.

Zander A., Fülling M.A., Brückner H., Mastronuzzi G., 2006. *OSL dating of Upper Pleistocene littoral sediments: A contribution to the chronostratigraphy of raised marine terraces bordering the Gulf of Taranto, South Italy*. Geografia Fisica e Dinamica Quaternaria, 29, 33-50.

(Ms. received 07 July 2023, accepted 10 October 2023)