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## Morphotectonics of the Tasso Stream - Sagittario River valley (Central Apennines, Italy)

E. Miccadei <sup>a,b</sup>, C. Berti<sup>c</sup>, M. Calista <sup>a</sup>, G. Esposito<sup>a</sup>, V. Mancinelli<sup>a</sup> and T. Piacentini <sup>a,b</sup>

<sup>a</sup>Department of Engineering and Geology, Laboratory of Tectonic Geomorphology and GIS, Università degli Studi “G. d’Annunzio” Chieti-Pescara, Chieti Scalo, CH, Italy; <sup>b</sup>Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy; <sup>c</sup>Department of Earth and Environmental Sciences, Leigh University, Bethlehem, USA

### ABSTRACT

This work presents the morphotectonic map of the Tasso Stream-Sagittario River valley, located in the Central Abruzzo area (Marsica region), in one of the areas of highest average elevation in the Apennines chain between two main intermontane basins (i.e. the Sulmona basin and Fucino basin). It is bounded by one of the main drainage divides of Central Italy, separating the Adriatic side of the Apennines from the large endorheic Fucino area. The morphotectonic map of the Sagittario River valley is the result of an geomorphological analysis of the drainage at the basin scale in Central Italy and incorporates three main sections: orography and hydrography (upper right on the map), the main morphotectonic map (center and left on the map), and the morphotectonic profile section (lower on the map). This map provides a basis for the recognition of morphotectonic features at the basin scale, the detection of tectonic vs. surface processes’ control on the landscape, and the reconstruction of the landscape evolution of the Sagittario gorges, one of the main gorges incising the carbonate ridges of the Apennines. It contributes to defining the main phases of the Quaternary landscape evolution of the inner mountain landscape of the Apennines, resulting from the combination of alternating morphotectonics (i.e. rock uplift and local tectonics) and surface processes (i.e. slope, karst, glacial and fluvial processes).

### ARTICLE HISTORY

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### KEYWORDS

Morphotectonic map; gorges incision; drainage evolution; Pleistocene; Central Italy

## 1. Introduction

An extensive geomorphological analysis of the drainage at basin scale in the Apennines chain and Adriatic piedmont of the Central Apennines (Italy) enabled the creation of morphotectonic maps (Miccadei, Orru, Piacentini, Mascioli, & Puliga, 2012; Miccadei, Piacentini, Gerbasi, & Daverio, 2012; Miccadei, Piacentini, Dal Pozzo, La Corte, & Sciarra, 2013; Santo et al., 2014; Piacentini, Sciarra, Miccadei, & Urbano, 2015). In this study, we present the morphotectonic map of the Tasso Stream-Sagittario River valley (Abruzzo, Italy) (scale 1:35,000) implemented within a GIS environment by means of (i) DEM- and map-based cartographic and morphometry analysis of orography and hydrography (raster and vector data scale 1:25,000 - 1:10,000, LiDAR data and 5 m grid DEM); (ii) photogeology analysis (scale 1:33,000); (iii) Quaternary continental deposits, fluvial terraces and geomorphological field mapping (scale 1:10,000); and (iv) morphotectonic profiles that couple landform, deposits and terraces.

The map incorporates three main sections:

- 1) orography and hydrography;
- 2) main morphotectonic map;
- 3) morphotectonic profile.

The main goals are to outline the morphotectonic features of the Tasso-Sagittario valley and to outline the landscape evolution of the Sagittario gorges and of the entire valley.

## 2. The study area

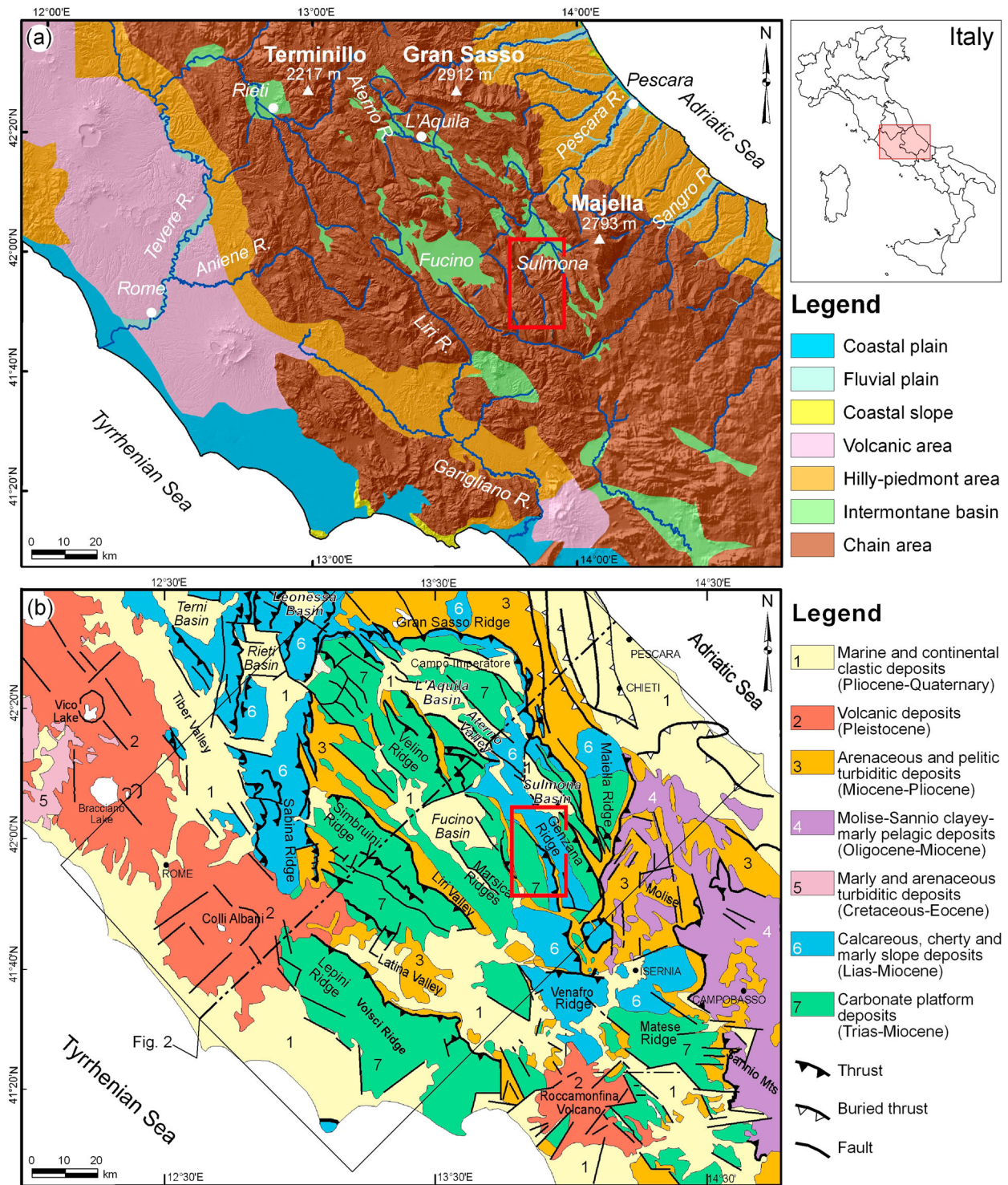
The Tasso Stream and Sagittario River, separated by the Scanno Lake, drain a valley located in the inner Central Apennines, in one of the highest average elevation areas in the entire chain. The valley runs parallel of one of the main drainage divides of the chain, between the Fucino endorheic basin and the Adriatic piedmont and coastal area (D’Agostino, Jackson, Dramis, & Funicello, 2001; Piacentini & Miccadei, 2014; Miccadei, Piacentini, & Buccolini, 2017) (Figure 1(a and b); Figure 2). This river is a tributary of the Aterno-Pescara River, the longest (and largest in terms of drainage basin) on the Adriatic side of the Apennines. It flows from the Western Marsica ridges and the Mt. Genzana ridge to the Sulmona intermontane basin (Figure 3).

The overall drainage basin lies within the core of the intricate geological and geomorphological framework of the Central Apennines, which is an asymmetric

**CONTACT** T. Piacentini [tpiacentini@unich.it](mailto:tpiacentini@unich.it) Department of Engineering and Geology, Laboratory of Tectonic Geomorphology and GIS, Università degli Studi “G. d’Annunzio” Chieti-Pescara, Via dei Vestini 31-66100, Chieti Scalo, CH, Italy; Istituto Nazionale di Geofisica e Vulcanologia, Sezione Roma 1, Via di Vigna Murata 605, 00143, Rome, Italy

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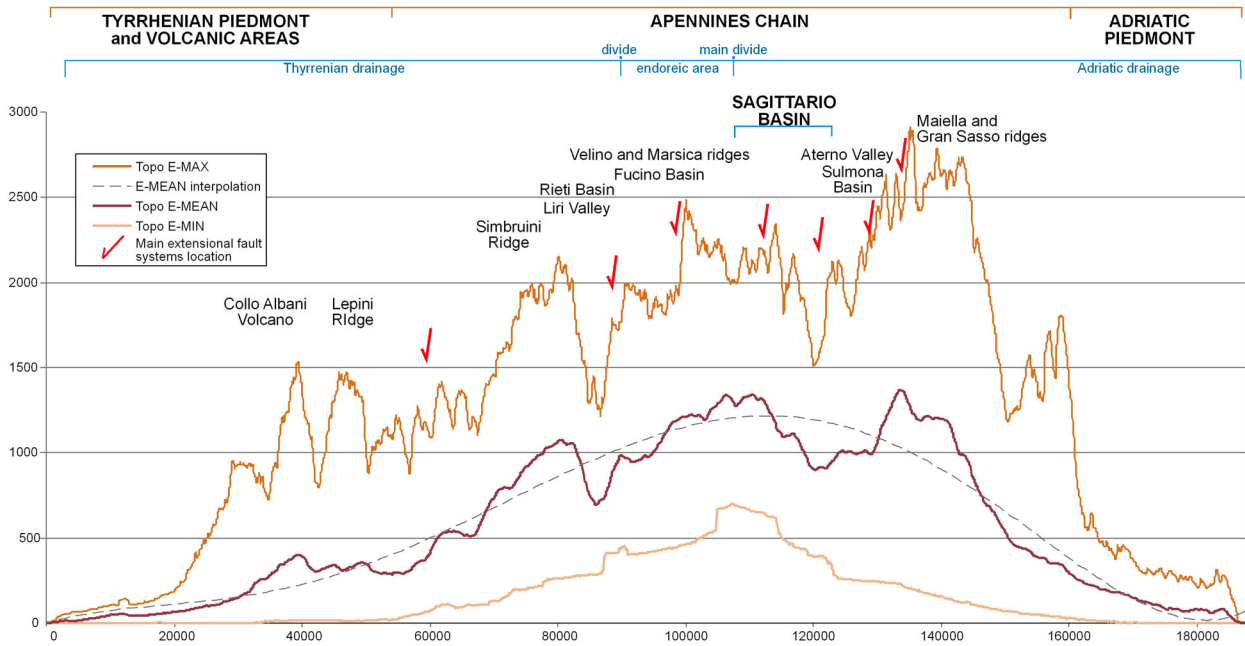
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**Figure 1.** (a) Location map of the study area (red box) in the physiographic setting of Central Italy. (b) Geological scheme of Central Italy. The study area is marked by the red box.

mountain range characterized by alternating ridges (up to 2900 m of elevation) and valleys with a NW-SE to N-S orientation, as well as transversal valleys and deep gorges. The chain comprises thrust sheets resulting from the deformation of Mesozoic–Cenozoic palaeogeographic domains (carbonate platforms and related margins, slope, and basin) consisting of pre-orogenic thick limestone and marl-limestone sequences. Orogenic compressional tectonics along NW–SE to N–S-oriented thrust-faults affected the

chain from the Late Miocene (western side) to the Pliocene (eastern side), with the formation of synorogenic pelitic arenaceous turbiditic sequences (Parotto, Cavinato, Miccadei, & Tozzi, 2004; Patacca & Scandone, 2007; Vezzani, Festa, & Ghisetti, 2010). This led to the emersion of the chain and the shaping of the incipient landscape composed of low hilly reliefs and islands, bordered by bays and small marine basins (Cipollari et al., 1999; Miccadei, D'Alessandro, Parotto, Piacentini, & Praturlon, 2014; Miccadei et al., 2017 and



**Figure 2.** Swath profile 190 km long and 100 km wide across Central Italy including the max, min and mean topography elevations of the Central Apennines chain (modified after Piacentini & Miccadei, 2014). It shows the location of the Sagittario drainage basin in the inner and highest mean-elevation area of the chain. The location (axis) and area of the swath profile is in Figure 1.



**Figure 3.** Panoramic views of the Sagittario River valley: (a) view from NW; (b) view from W; (c) view from N.

references therein). Compressional deformation was followed by strike-slip tectonics along mostly NW–SE to NNW–SSE-oriented faults (Corrado, Miccadei,

Parotto, & Salvini, 1996; Miccadei et al., 2014). Since the Early Pleistocene (particularly during the Middle Pleistocene), the orogen underwent regional uplifting

(Ascione & Cinque, 1999; Ascione, Cinque, Miccadei, Villani, & Berti, 2008; Aucelli et al., 2011; Carminati & Doglioni, 2012; D'Agostino et al., 2001; Giano & Giannandrea, 2014). Contemporaneously, local extensional tectonics affected the chain from the western areas to the east along the main NW–SE-trending extensional fault systems. This caused dissection of the chain system, the formation of the intermontane basins (i.e. Fucino Plain, Sulmona Basin; Bonini, Di Bucci, Toscani, Seno, & Valensise, 2014; Cavinato & De Celles, 1999; Cavinato, Carusi, Dall'Asta, Miccadei, & Piacentini, 2002; Galadini & Messina, 2004; Giaccio et al., 2012; Giano, Gioia, & Schiattarella, 2014; Gori, Falcucci, Ladina, Marzorati, & Galadini, 2017; Miccadei, Barberi, & Cavinato, 1999; Miccadei, Carabella, Paglia, & Piacentini, 2018; Piacentini & Miccadei, 2014), and the emersion of the Adriatic piedmont and coastal area (Ascione et al., 2008; Buscher, Ascione, & Valente, 2017; Miccadei, Mascioli, & Piacentini, 2011; Miccadei, Mascioli, Ricci, & Piacentini, 2019; Miccadei et al., 2017).

The Sagittario River basin incorporates a 48-km-long main river. In the upper southern region, it is called Tasso Stream and flows in a roughly S–N orientation into the Scanno Lake. Downstream of the Scanno Lake, the Sagittario River flows through and incises the Sagittario gorges in a SE–NW orientation parallel to the main ridges (Montagna Grande, Mt. Genzana), and then, after a sharp turn, makes a SW–NE wide incision transversal to the main ridges.

The main valleys are deeply carved into the Montagna Grande and Mt. Genzana ridges over a carbonate bedrock from different Mesozoic–Cenozoic paleogeographic units. Here, the eastern margin of the Lazio–Abruzzo carbonate shelf is tectonically juxtaposed to the calcareous-marly Mount Genzana slope-to-basin domain along a major NNW–SSE tectonic lineament (Profluo–Tasso–Sagittario line, Miccadei, 1993; Corrado et al., 1996; Miccadei et al., 2014), historically known (Beneo, 1938). From the late Miocene onwards, the abovementioned domains have been affected by deformation, which has resulted in pervasive faulting: the Late Miocene–Early Pliocene thrusting (Montagna Grande thrust), the Pliocene strike-slip tectonics (Mt. Genzana–Masserie fault), and the Pleistocene normal faulting (reactivation of the Mt. Genzana–Masserie fault). During the Quaternary, sequences of continental glacial, slope, alluvial fan and fluvial deposits were formed (Miccadei et al., 2014).

The overall landscape is characterized by alternate wide valleys along with deep incisions and gorges (Figure 3) and is related to the drop in the base level of the Sulmona basin, tectonically induced (Berti, 2008; Ciccacci, D'Alessandro, Dramis, & Miccadei, 1999; Piacentini & Miccadei, 2014). It is largely characterized by structurally controlled landforms and fluvial landforms related to the incision, whereas the highest

elevations areas (>1500 m a.s.l.) are largely affected by karst landforms and glacial features (inheritance of the Pleistocene glacial stages).

A distinctive element in the architecture of the basin is the Scanno landslide. This is a large rock avalanche ( $\sim 90 \times 10^6 \text{ m}^3$  of limestone and subordinate flysch) detached from the eastern side of the main valley (Mt. Genzana), that dammed the upper part of the valley, thus causing the impoundment of Scanno Lake (Bianchi Fasani et al., 2011; Della Seta et al., 2017; Nicoletti, Parise, & Miccadei, 1993; Scarascia Mugnozza et al., 2006).

### 3. Methods

The morphotectonic map of the Sagittario River basin is the result of a geomorphological analysis at a drainage basin scale, which was produced with (i) cartographic analysis and morphometry of orography and hydrography (on raster and vector data scale 1:25,000 - 1:5,000; vector map-derived 5 m DEM (Digital Elevation Model); 1 m LiDAR-derived DEM), (ii) photogeology analysis (scale 1:33,000), (iii) field mapping of Quaternary continental deposits and structural geomorphological (scale 1:10,000), and (iv) morphotectonic transversal and longitudinal profiles.

On the DEM, slope analysis and local relief analysis (*sensu* Ahnert, 1984, elevation range on a  $1 \times 1 \text{ km}$  window) were performed (Burbank & Anderson, 2011).

The hydrographic analysis allowed the definition of drainage patterns, knick-point distribution, and steepness (Ksn) parameter (Burbank & Anderson, 2011; Horton, 1945; Strahler, 1957; Whipple, 2004; Wobus et al., 2006).

The photogeology analysis allowed the mapping of the main landforms for the entire Sagittario River valley using 1:33,000 scale aerial photos and 1:10,000 color orthophoto images.

The Quaternary continental deposits, main tectonic elements and morphotectonic elements (ridges, slopes, valleys, and hydrography) were investigated using a 1:10,000 scale structural geomorphological field mapping according to the first morphotectonic studies in Italy (Ambrosetti et al., 1987; Ciccacci, Fredi, Lupia Palmieri, & Salvini, 1986; ENEL, 1981; Panizza & Castaldini, 1987; Lupia Palmieri et al., 1996) along with a more recent morphotectonic approach (Amato et al., 2018; Bianchi et al., 2013, 2015; Brogi & Liotta, 2008; Burbank & Anderson, 2011; Chelli, Segadelli, Vescovi, & Tellini, 2016; Miccadei, Paron, & Piacentini, 2004; Picotti, Ponza, & Pazzaglia, 2009; Smith, Paron, & Griffiths, 2011; Scotti, Molin, Faccenna, Soligo, & Casas-Sainz, 2014).

The results are correlated and discussed in terms of geomorphological evolution of the gorges, through a longitudinal profile, projecting morphotectonic

elements, continental deposits, and knick-points. Each feature is located along the profile according to its distance from the outlet and the symbols are rotated taking into account the angle with the valley axis. The deposits and the main morphotectonic elements are also projected in the profile at actual elevation in order to outline their correlation. The depth of the deposits along the valley-floor is geomorphologically inferred and verified through boreholes.

## 4. The morphotectonic map

### 4.1. Orography and hydrography section

The overall orographic setting of the basin is characterized by high mountain ridges (up to Mt. Marsicano, 2254 m a.s.l.) and by the main valley. The slopes are up to >200% of average steepness with several vertical escarpments while the relief energy ranges from 200 m to >900 m, outlining a strong dissection of the landscape.

The longitudinal profile of the Tasso-Sagittario valley shows four main concave reaches, separated by sharp knick-points or bends (Figure 4). Starting from the south, the upstream S-N reach (Sector 1 – Godi Mountain area) is a wide, smooth valley from the Serra Ziomias area to the S. Liborio area (knick-point a); it ranges from 1740 m to 1150 m a.s.l. The upper intermediate SE-NW reach (Sector 2 – Scanno Lake area) extends from the S. Liborio area to Scanno Lake (knick-point b) carving the minor Tasso gorges and ranges from 1150 m a.s.l. to 923 m a.s.l. The lower intermediate SE-NW reach (Sector 3 – Sagittario gorges area, ranging from 900 m a.s.l. to 550 m a.s.l.) is again concave from the Scanno landslide, which dammed the Tasso Valley, to the sharp bend in the Anversa area; a sharp knick-point (c) occurs 1.0 km upstream from the bend. The downstream SW-NE reach (Sector 4 – Sulmona Plain area) runs from the sharp bend of the Anversa to the Sulmona Plain, transversal to the main ridges and valleys, ranging from to 550 m a.s.l. to 323 m a.s.l.

The overall drainage network is characterized by different patterns: a trellis pattern in the SE and NW part of the basin, sub-dendritic and sub-parallel patterns in the central sector along the main and deep valleys, and angular pattern in the western area.

### 4.2. The main morphotectonic map section

Lithology, main tectonic features, and morphotectonic elements are shown in the main morphotectonic map.

#### 4.2.1. Lithology

The lithology units are listed in the following paragraphs, from the oldest to the youngest (with numbers referring to the map).

**4.2.1.1. Mesozoic-Cenozoic marine calcareous bedrock (9-10).** It is composed of Jurassic (Triassic?) to the Miocene pre-orogenic rocks (Miccadei, 1993; Miccadei et al., 2014; Patacca & Scandone, 2007; Vezzani et al., 2010), grouped according to the original paleogeographic domain. Calcareous micritic and calcarenitic-calciruditic units (10) pertain to the Lazio-Abruzzo carbonate platform and shelf domain, while the calcareous-siliceous-marly units (9) originated in the Genzana slope-to-basin domain.

**4.2.1.2. Neogene marine pelitic-arenaceous bedrock (8).** A single unit incorporates all the Upper Miocene-Lower Pliocene pelitic-arenaceous rocks sedimented during the formation of the Apennines in foredeep marine environment. They consist of alternating sandstone and pelitic layers, except for the Anversa area, where clays with thin sandstone levels and gypsum layers occur (Miccadei, 1993; Miccadei et al., 2014; Patacca & Scandone, 2007; Vezzani et al., 2010).

#### 4.2.1.3. Quaternary continental deposits (from 7 to 1).

The Quaternary continental deposits are arranged in seven main units (Figure 5), from the Lower Pleistocene to the Holocene, separated by unconformity

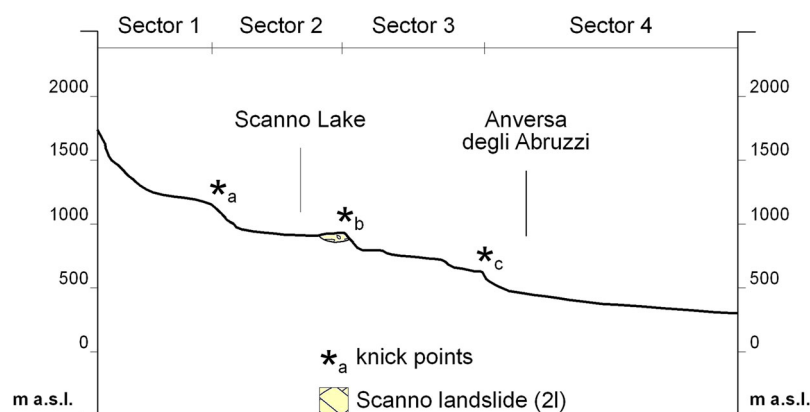
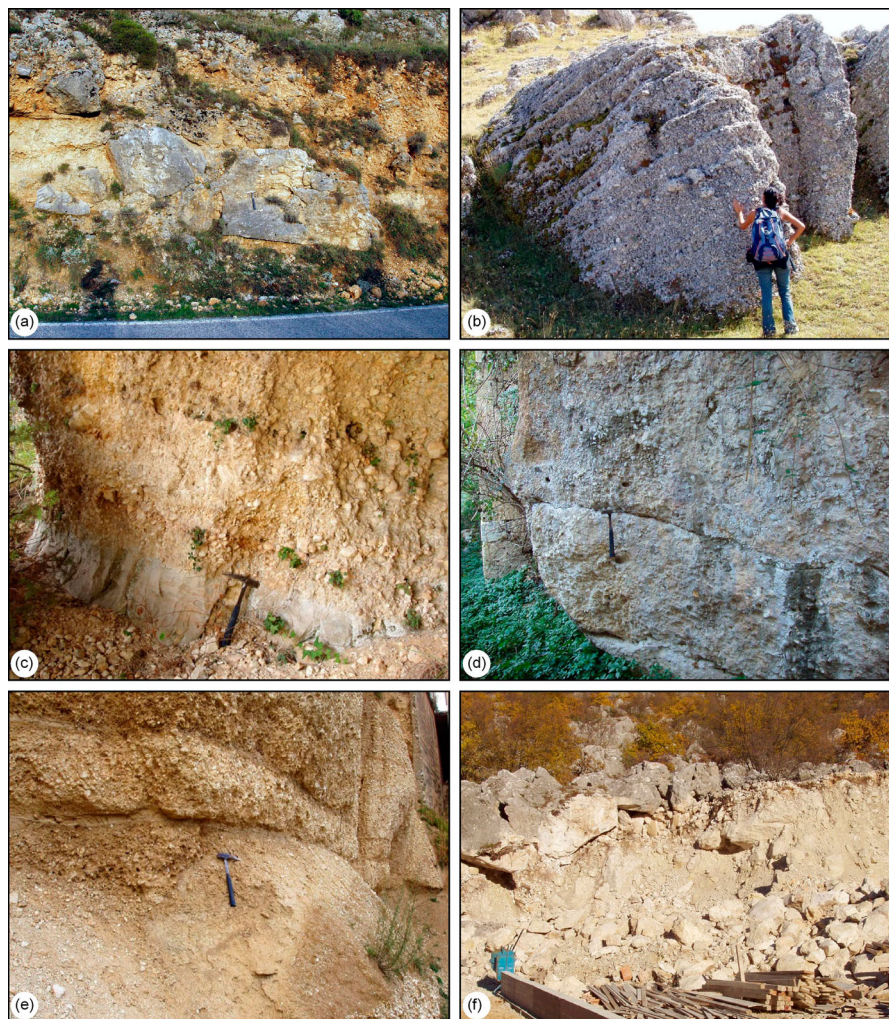


Figure 4. Longitudinal profile of the Tasso Stream-Sagittario River.



**Figure 5.** Quaternary continental deposits of the Sagittario valley. (a) Frattura (1175 m a.s.l.). Heterometric breccia that contains large calcareous boulders (up to 1 m in size) in the lower part of the deposit (7s); (b) Serra di Ziomas (1610 m a.s.l.). Well-stratified and heterometric breccia (7s); (c) Scanno. Heterometric conglomerate, well-cemented, with sandy and silty lenses and thin levels (6f); (d) Anversa degli Abruzzi (550 m a.s.l.). Conglomerate consisting of 1–10 cm in size, from sub-rounded to well-rounded clasts, arranged in 2–3 m thick bank (4a); (e) Scanno (1000 m a.s.l.). Calcareous conglomerate, with a silty-sandy matrix, containing sandy levels and lenses (3f); (f) Sagittario valley (920 m a.s.l.), east of the Villalago center. Chaotic accumulation of very large calcareous blocks, refer to Scanno landslide deposits (2 l).

boundaries (UBSU, Salvador, 1994), which are modified from APAT (2006) and ISPRA (2014). Each unit may incorporate different types of deposits, according to their genetic geomorphological processes (i.e. slope, landslide, fluvial, alluvial fan, colluvial, glacial, and karst). The units and deposits (listed and described in the legend of the map) consist mainly of calcareous breccia, conglomerate, and gravel, with interbedded sand and sandstone (Figure 5). The age of the units is from the Lower Pleistocene to the Holocene and is constrained by geomorphological correlation to dated deposits but also supported by palaeosols and lithic industries (see the scheme of Quaternary continental deposits in the map; modified from Miccadei et al., 2014). The arrangement of these units is summarized in the transversal morpho-lithostratigraphic schemes (Main Map). The units are placed on the slopes at a different elevation above the present thalweg up to the top of some minor ridges and deeply

entrenched into one another. In the eastern side of the valley (Frattura area), the Lower Pleistocene deposits are also affected by normal faulting (along the Mt. Genzana-Masserie fault).

#### 4.2.2. Tectonic features

The main tectonic features in the Tasso-Sagittario basin are thrust faults, strike-slip faults, and normal faults. The main thrust fault (Montagna Grande thrust) is NNW-SSE oriented (low angle WSW dipping), located in the western side of the valley, and is largely displaced by subsequent high angle faults. The main high angle fault system with strike-slip component (Genzana-Masserie valley fault) is from NNW-SSE to NW-SE oriented and is located in the eastern side of the valley. Finally, the normal fault systems are mostly NW-SE oriented (and occasionally SW-NE). They pervasively affect the calcareous ridges (e.g. Montagna

Grande-Mezzana area, Prezza area) and locally reactivate the Genzana-Masserie fault.

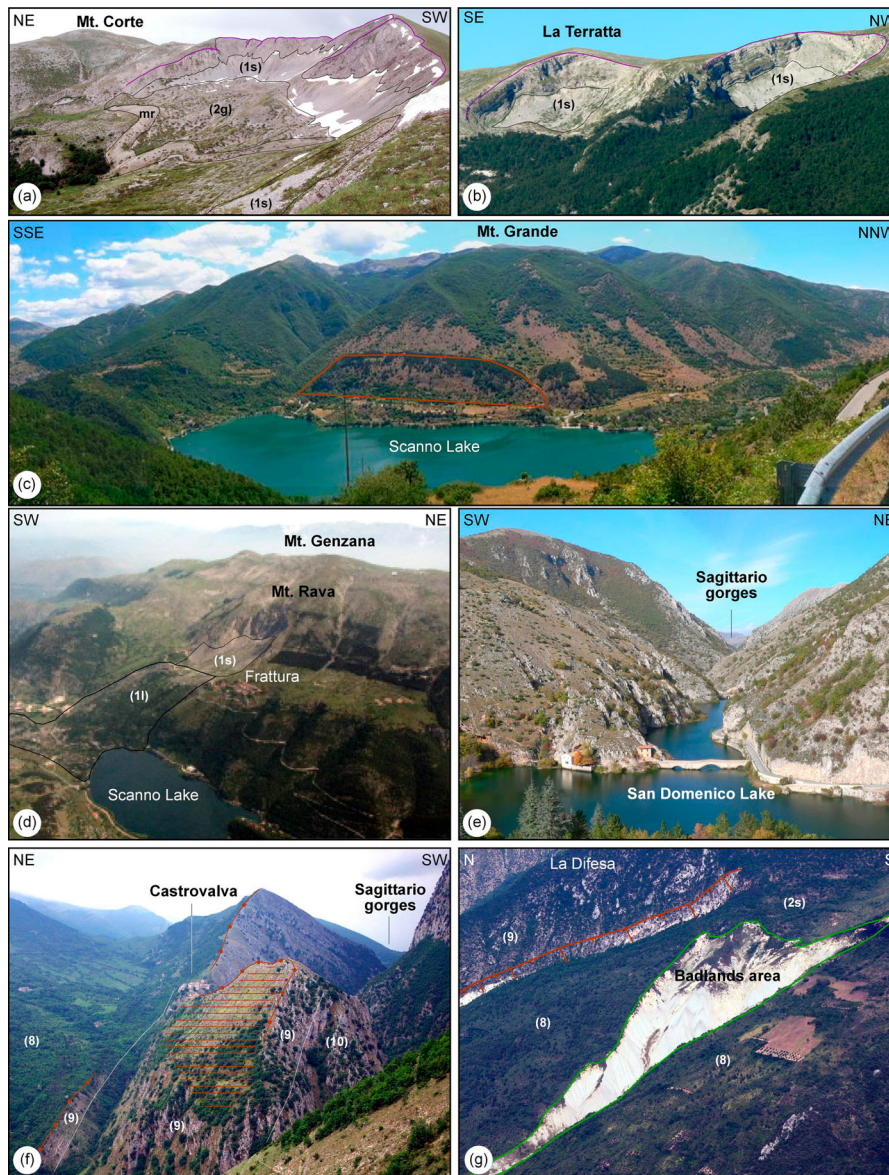
**4.2.3. Morphotectonic elements**

The types, location, orientation, and nature of the mapped landforms show a distinctive distribution in the main sectors of the valley.

Sector 1 (Godi Mountain area). This sector is characterized by two main valleys (Tasso Valley and Vallone delle Masserie), deeply incised in the pelitic-arenaceous bedrock (bottom of the valley) with steep slopes on the calcareous bedrock. These valleys show mostly S-N (Tasso Valley) and SE-NW orientation (Vallone delle Masserie) and are bounded by two main systems of fault line escarpments. The main valleys are mostly U-shaped in the upper part and become deep and V-shaped in the lower part at the boundary

with Sector 2, corresponding to a main hanging valley (knick-point a). The slopes of the valleys are characterized by vertical rock escarpments and step-like slopes, related to the lithostructural control of the thick layers in the carbonate bedrock. The ridge between the Tasso Valley and Vallone delle Masserie shows a gentle summit area (~1650–1700 m a.s.l.) largely affected by karst landforms. In the highest part of the area (Mt. Marsicano), NE-facing minor valleys feature glacial cirques (>1800 m a.s.l.) and moraine ridges in the valley bottoms (Figure 6(a and b)).

Sector 2 (Scanno Lake area). The Tasso gorge is developed in a SE-NW orientation downstream of the uppermost knick-point (a; Figure 4) and features a deep V-shaped valley. Downstream, the bottom of the main valley is carved on the Neogene marine pelitic-arenaceous bedrock largely covered by continental



**Figure 6.** Morphotectonic elements of the Sagittario valley. (a) Glacial cirques and moraine ridges of Mt. Corte (Sector 1); (b) Glacial cirques of Mt. La Terratta (Sector 1); (c) Trapezoidal facets (Sector 2); (d) Scanno rock avalanche (Sector 2); (e) Sagittario gorges (Sector 3); (f) Ridges and structural surface of the Castrovalva (Sector 3); (g) “Il Caccavone” badlands area (Sector 4). The numbers in the photos refer to the lithological legend of the main map.

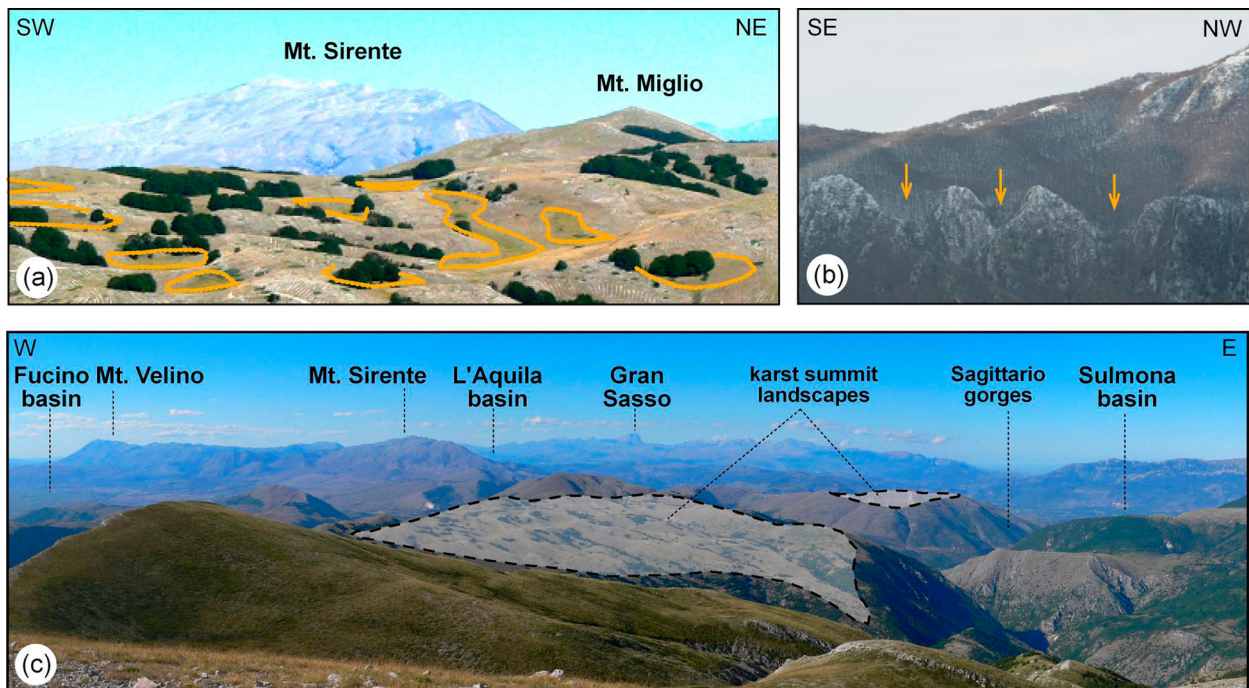


deposits, landslide deposits and the Scanno Lake. Triangular and trapezoidal facets characterize the SW slope, while the NE slope features triangular facets and fault line scarps. The only evidence of a fault escarpment is in the Frattura area. The Scanno landslide, which shows typical rock avalanche features, affected the eastern fault line escarpment of the valley and is largely controlled by the Mt. Genzana fault (Figure 6(d); Bianchi Fasani et al., 2011; Della Seta et al., 2017; Nicoletti et al., 1993; Miccadei et al., 2014; Scarascia Mugnozza et al., 2006). Glacial cirques are present in the western area as well as in Sector 1.

Sector 3 (Sagittario gorges area). This sector is characterized by the SE-NW Sagittario gorges, which deeply incised in the calcareous bedrock (Figure 6(e)). On the other hand, a large hanging valley, with large saddles aligned in a SE-NW orientation, runs parallel to the gorges carved in the pelitic-arenaceous bedrock and along the Genzana fault. The main morphotectonic features are related to selective erosion (i.e. hogbacks, large fault-line escarpments). The most outstanding features are at sector 3 - sector 4 transition: the hogback between the Sagittario gorge and the eastern hanging valley (Figure 6(f)); a large NW-SE-oriented fault-line escarpment along the Genzana fault (Figure 6(g)); and the associated large badland, with a length of ~1.2 km, over an elevation range of 350 m, a depth up to >50 m and an area of ~120,000 m<sup>2</sup> (Figure 6(g)). The main gorge is rimmed by straight ridges (mostly in NNW-SSE directions), wind gaps, and structural scarps, along with two main SW-NE

hanging valleys in the western area, outlining a strong dissection. A large karst area with several dolines (Figure 7(a)) and sinkholes (NW-SE-oriented and aligned along minor faults) is present in the western side of the valley on top of the ridge (at 1650–1500 m a.s.l.). Toward the Sagittario gorges, this karst area features half preserved dolines and eroded sinkholes outlining the incision of a former karst landscape along the gorges (Figure 7(b)). This suggests that the dissection of the gorges is related to the dissection of the karst landscape (Figure 7(c)). In addition, the slopes of the valleys are characterized by landslides, including rock falls and rock avalanches (as close to the main knick-point c). The overall features outline that Sector 3, particularly at the transition with Sector 4, is the most affected by deep incision and landscape dissection processes.

Sector 4 (Sulmona Plain area). The NE sector of the study area is characterized by a wide SE-NW valley carved in the Neogene marine pelitic-arenaceous bedrock (a continuation of the SE-NW main hanging valley of Sector 3). After the sharp bend at Anversa degli Abruzzi, the Sagittario River transversally intersects the wide valley and cuts a V-shaped valley into the Mt. Prezza–Mt. Genzana ridge. Towards the Sulmona basin, the valley is remarkably rectilinear (possibly connected to minor SW-NE faults) and the units 3 and 2 are arranged in two orders of terraces. Main features are straight valleys, river bends, fluvial erosion scarps and a karst area in the ridges of Mt. Catini and Mt. Pietrafitta (1000–1500 m a.s.l.).



**Figure 7.** Karst features of the Sagittario valley. (a) Karst area and dolines of Mt. Miglio; (b) Half preserved dolines, on the NE slope of Mt. Miglio; (c) Panoramic view of the summit area of the Sagittario River valley incised between the Fucino, L'Aquila and Sulmona basins outlining the karst summit landscapes (white area) incised by the main gorges.

### 4.3. The longitudinal profile section

The profile summarizes the main morphotectonic features of the four different sectors.

Sector 1 (Godi Mountain area) includes the upper part of the basin down to the first main knick-point (a; [Figure 4](#)) corresponding to a major hanging valley. This is associated with the tectonic contact between pelitic-arenaceous rocks (upstream) and calcareous rocks (downstream) in which the Tasso gorges are incised. The entrenchment suggests a local relief inversion since the lower and deeper part of the valley (Sector 2) is incised in hard calcareous rocks. Karst landforms are widespread, with most on gentle surfaces located at 1650–1700 m a.s.l. The upper part of the valley is characterized by the oldest continental units (Zio-mas Unit - 7, Lower Pleistocene), placed at ~300 m above the valley bottom (1750–1480 m a.s.l.) and entrenched below the karst surface. The Upper Pleistocene (moraine “2g” and slope deposits “2s”) and Holocene (slope “1s” and fluvial deposits “1f”) units are along the valley bottom or slightly incised by the present river (1530–1230 m a.s.l.).

Sector 2 (Scanno area) corresponds to the Tasso gorges (over calcareous bedrock) and to the Scanno Lake area (over pelitic arenaceous bedrock). Large bodies of ancient continental deposits are preserved in this area (the Scanno Unit - 6, Lower Pleistocene), placed at ~250 m above the present valley bottom (1450–1200 m a.s.l.). More recent deposits associated with the Sulmona Unit - 3 (Middle Pleistocene) are entrenched in the previous units and hang ~70 m above the present valley bottom, while deposits from the Holocene to the present day conform to the valley bottom. The downstream boundary of this sector is marked by the second knick-point (b; [Figure 4](#)), which is again related to a lithologic tectonic contact (pelitic-arenaceous rocks in the upstream area, under Scanno Lake, and calcareous rocks in the downstream area) at the entry point of the Sagittario gorges. As described before, the deep gorges are incised on the more resistant calcareous rocks. Moreover, the knick-point was further enhanced by the occurrence of the Scanno landslide dated back to the late Upper Pleistocene or Lower Holocene ([Miccadei et al., 2014](#); [Scarcia Mugnozza et al., 2006](#)).

Sector 3 (Sagittario gorges area) includes the entire Sagittario gorges, which are rimmed by sharp structurally controlled escarpments and hogback ridges (1300–1600 m a.s.l.). The karst area is located at the top of the SW ridges at ~1600 m a.s.l. It incorporates several half-preserved dolines and eroded sinkholes, as well as two main SW-NE hanging valleys. These features are located along the gorges’ edge ~800 m above the valley bottom and above the highest continental deposits (7f,s and 5s, Lower-Middle Pleistocene) found in Sectors 2 and 4. Below these morphostructural

features and within the gorges, almost no continental deposits are preserved except for patches of Holocene slope, landslides and fluvial deposits (1 l,s) along the valley bottom and slopes. Very small patches of alluvial fan deposits are preserved at ~70 m above the valley bottom (correlated to the Anversa unit - 4 along the profile, in terms of elevation, gradient, and height above the valley bottom). Moreover, at the outlet of the gorges (Anversa degli Abruzzi), late Middle Pleistocene alluvial fan deposits (Anversa Unit - 4) are preserved at ~100 m above the present valley bottom. The third major knick-point (c; [Figure 4](#)) is close to the downstream end of the Sagittario gorges, 1 km away from the major river bend and the lithological tectonic contact (with calcareous rocks upstream and pelitic-arenaceous rocks downstream). The gorges’ profile testifies that this area, as mentioned above, experienced a strong dissection during the Pleistocene. The first dissection occurred before the formation of the Lower Pleistocene deposits, incising the high elevation karst landscape along main or minor tectonic features (instead of the more erodible arenaceous-pelitic bedrock). During the Lower-Middle Pleistocene, the gorges were a by-pass erosive incision due to fluvial and karst processes between Sectors 2 and 4. At the end of Middle Pleistocene, the gorges’ bottom should be at ~100–50 m above the present valley bottom (Anversa and Sulmona units). Finally, the incision reached the present configuration (Upper Pleistocene-Holocene) inducing the formation of large slope deposits, rock falls and large landslides on the slopes, which now control the present valley long profile (i.e. knick-point c).

Sector 4 (Sulmona Plain area) is developed from the outlet of the Sagittario gorges through the transversal (SW-NE) Sagittario Valley, which is clearly aligned with a major SW-NE hanging valley in the Mt. Mezzana ridge (1500 m a.s.l.) at the boundary between Sectors 3 and 4, with possible inheritance of a SW-NE ancient drainage before the incision of the Sagittario gorges and a control of minor faults as those present on the slopes of the valley. The deposition of a sequence of entrenched continental deposits and a flight of two alluvial fan and fluvial terraces occurred after the incision of the gorges in this area. The Middle Pleistocene deposits (Mezzana Unit - 5) hang on the slopes (at ~200 m a.s.l. above the present valley bottom); late Middle Pleistocene deposits are remnants of an alluvial fan (the apex) at the mouth of the gorges (100 m above the valley bottom, Anversa Unit - 4) and of terraced fluvial deposits along the valley (70 m above the valley bottom, Sulmona Unit - 3); Upper Pleistocene (Introdacqua Unit - 2, 50 m above the valley bottom) and Holocene alluvial fan and fluvial deposits (1a and 1s) are entrenched into the present valley.

## 5. Discussion and conclusion

The morphotectonic map presented in this work provides a contribution to the definition of the landscape evolution of a high elevation mountainous area in the Apennines chain. The Tasso-Sagittario valley is the result of alternating morphotectonics and surface processes, due to rock uplift processes, local tectonics (with the lowering of the local base level in the Sulmona outlet) and mainly slope, karst, and fluvial processes. The main valley is a complex fault-line valley developed along the Mt. Genzana-Masserie major fault system and the Montagna Grande thrust fault. It mainly is associated with the erosion of pelitic-arenaceous bedrock between them but also to the dissection of the Sagittario gorges into the Mesozoic-Cenozoic calcareous bedrock. Evidence of fault escarpments with possible Quaternary fault activity is only present in Sector 2 (i.e. Frattura).

The Sagittario gorges are a 7.5 km long gorge area up to >500 m deep incised in the calcareous bedrock due to a combination of fluvial and karst processes, which led to the rearrangement of the drainage of the valley. The main steps of the gorges evolution can be summarized as follows:

- Dissection of the karst summit landscape as testified by half-preserved dolines and hanging valleys (possibly before the Lower Pleistocene; Figure 7), with the first phase of the incision of the gorges and rearrangement of the drainage with a sharp bend from SW-NE (Mezzana major hanging valley) to SE-NW;
- Incision of the gorges into the calcareous rocks combining karst and fluvial processes (controlled by tectonic features) during the Lower and Middle Pleistocene, with prevailing erosive processes and sediment bypass (as seen in the Ziomas Unit or Scanno Unit);
- Formation of an alluvial fan (Anversa Unit) at the outlet of the gorges during the late Middle Pleistocene, with the valley bottom lying at ~50–100 m above the present valley floor;
- Incision of the present valley (Upper Pleistocene-Holocene) inducing the formation of large slope deposits, rock falls and large landslides on the slopes, which control the present valley's longitudinal profile. The Scanno landslide changed the configuration of the middle part of the whole basin in the last evolutionary phases, separating the Tasso Stream and Sagittario River with the formation of the Scanno Lake.

## Software

The map presented in this work was produced in the Geographic Information System ArcGIS® 10.6 (ESRI).

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## ORCID

E. Miccadei  <http://orcid.org/0000-0003-2114-2940>  
 M. Calista  <http://orcid.org/0000-0002-4525-5395>  
 T. Piacentini  <http://orcid.org/0000-0002-5007-7677>

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