Available online http://amq.aiqua.it
ISSN (print): 2279-7327, ISSN (online): 2279-7335

Work presented during the AIQUA scientific conferences
"Waiting for the Nagoya INQUA XIX Congress", held in Florence, June 18 - 19, 2015

QUATERNARY EVOLUTION OF THE FLUVIOKARST ROSANDRA VALLEY (TRIESTE, NE ITALY)

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ABSTRACT: The stratigraphy of terraced sediments as well as morphological features of the middle reach of the Rosandra Valley (Trieste, NE Italy) were studied in order to reconstruct its Quaternary evolution. This sector forms a fluviokarst valley, which is characterized by a deep incised gorge with abrasional features. Downstream, the gradient is reduced, the valley widens and terraced deposits occur.
Alluvial/colluvial terraces crop out for about 1 to 1.5 km along the creek. They show the coalescence of the alluvial deposits with debrisfalls from the steep limestone slopes and colluvial fans related to some minor tributaries. The highest terrace is roughly 15 m high.
^{14}C datings on a frustule plant collected in the lower part of the deposit (> 45.000 yrs. BP), together with geological and geomorphological considerations, suggested that the terrace scarp could be Middle Pleistocene in age. The geomorphic regime of the creek changed from aggradation to erosion, as recorded by fanhead trenching and incision of fluvial terrace scarps, and it still persists. The tectonic uplift, which is partly responsible for the downcutting of the terrace and is still active, could be related to the SE-NW tilting of the Karst plateau.

Keywords: Alluvial terraces, fluviokarst valley, karst gorges, terra rossa, NE Italy.

1. INTRODUCTION

The Rosandra Valley (Glinščica), located at the north-eastern side of the Adriatic Sea (Fig. 1a), is a fluviokarst valley (Cucchi et al., 2009). This kind of fluvial system responds to tectonics, climate and sea-level change (Schumm, 1977; Jones et al., 1999). Fluviokarst forms develop mostly in the first stages of karstification in areas of intensive rainfall, when discharge into the karst system exceeds its conduit system capacity (Dreybrodt & Gabrovšek, 2002). Carving processes are dominant in the upper part of the valley, while depositional processes prevail in the lower part; the profile is generally steeper near the watershed divide, while it is gentler at the mouth of the valley (Leopold et al., 1964). The Dinaric Karst is dominated by fluviokarst valleys, with alternate intermountain basins, deep canyon and gorges (Roglić, 1972), such as the valleys of the Krka River in Dalmatia or the Vela Draga in Istria (Miracle & Forenbaher, 2005). Lepirica (2015) suggested the influence of the structural setting in the development of many gorges in the Central Dinarides. On the contrary, floodplains are absent or confined in poljes (Žebre et al., 2016) and terraces are usually fragmentary (Bognar et al., 2012). Many studies (e.g. Aley, 1965; Sanders, 1981; Palmer, 1991; Bognar et al., 2012; Woodside et al., 2015) have shown that physical erosional processes may also play an important role in the formation of these systems.

The Quaternary deposits and the reconstruction of the evolution of fluviokarst valleys in the eastern Adriatic were almost neglected. The study of such valleys can provide an important contribution regarding the evolution of fluviokarst valleys in the Dinaric area. In the study area, Frisia et al. (2005) studied a speleothem in the Gualtiero Savi cave in order to reconstruct the Holocene climate change, while Finocchiaro et al. (2015) described the sedimentological features of the stratigraphic sequence of the terrace here reported and they tentatively dated it from the Eemian (MIS5e) to MIS2. It represents the only exposed Quaternary sequence in the Italian sector of the Classical Karst Region. Quaternary deposits inside the nearby the Grotta degli Orsi cave were studied by Berto & Rubinato (2013), who reported the presence of *Ursus Spelaeus* on the floor surface and the walls.

Carulli et al. (1980) highlighted the occurrence of a Plio-Quaternary SE-NW tilting of the Karst plateau, from Trieste to the northern sector of the Gulf of Trieste (Fig. 1). The tilting was studied in detail along the coast using geomorphological, sedimentological, archaeological sea level markers and geophysical data (e.g. Antonioli et al., 2004, 2007; Furlani et al., 2011; Carulli, 2011; Biolchi et al., 2016). These studies suggested that the city of Trieste is tectonically stable (Melis et al., 2012), while the coast subsided moving toward NW. According to Braitenberg et al. (2005) the tilting is still active. Topographical and geomorphological indicators also underline a decrease in the elevation of the structural scarp in correspondence to the limestone-flysch contact toward NW (Furlani et al., 2011).

In this paper, we aim at discussing the Quaternary paleogeographic evolution of the middle sector of the Rosandra Valley (Fig. 1) using remote, field and laboratory data in the context of the Gulf of Trieste.

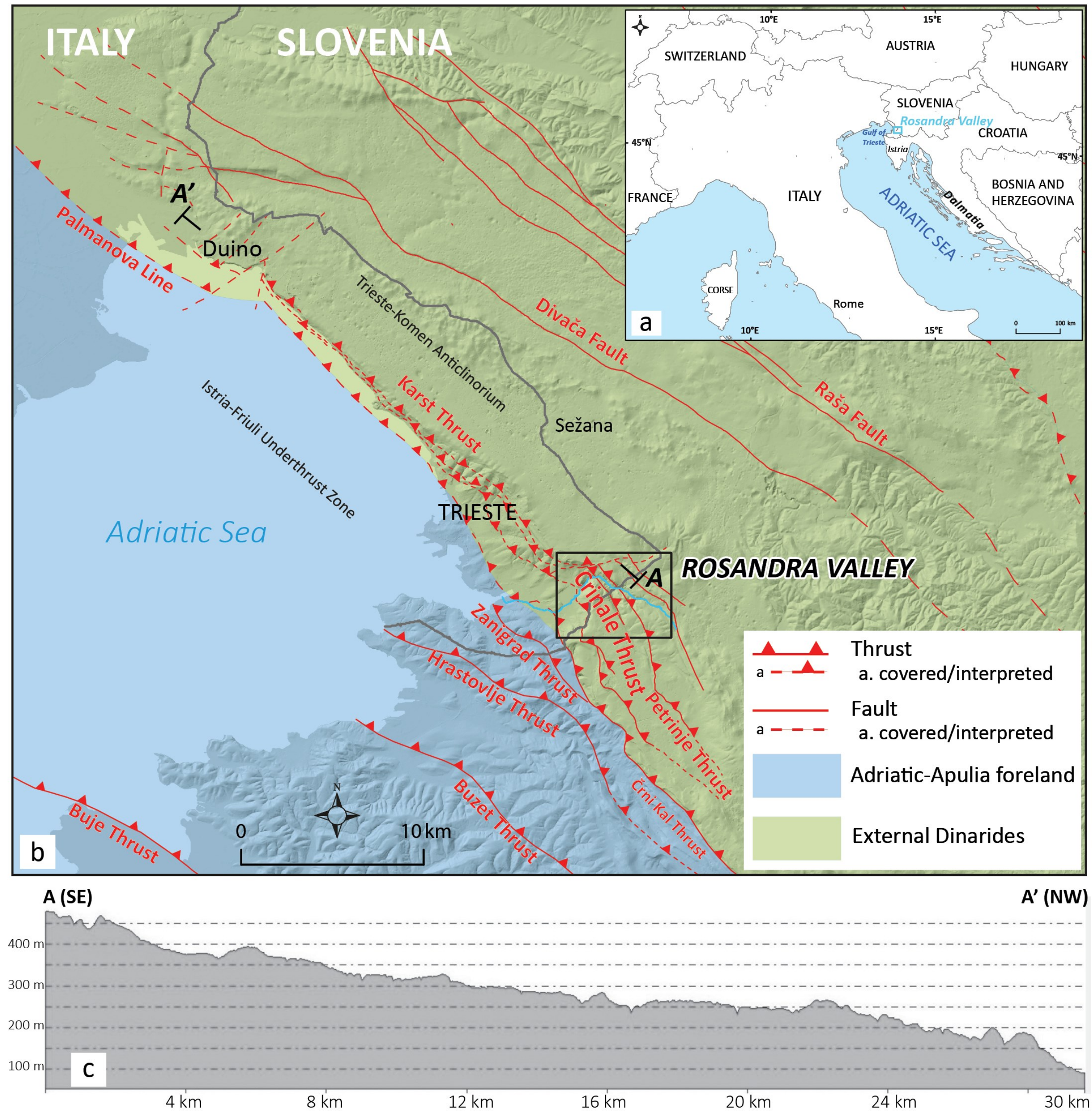

Fig. 1 - a) Geographical setting of the study area.; b) Geodynamical framework of the Classical Karst Region; c) SE-NW profile, that highlights the topographic trend of the karst plateau related to the tilting, which develops in the same direction (the profile was produced using SRTM data - Shuttle Radar Topography Mission, http://www2.jpl.nasa.gov/srtm/).

2. STUDY AREA

The study area belongs to the External Dinarides and is located in the southwestern side of the Classical Karst Region. This sector is characterized by NW-SE oriented thrust and fault systems and is defined as *Trieste-Komen Anticlinorium* (Placer et al., 2010; Fig. 1b). The western border of the Classical Karst Region facing the Gulf of Trieste is characterized by the occurrence of the Dinaric frontal ramp system (Busetti et al., 2010). The latter is constituted by the NW-SE segments of the Palmanova Line (Carulli, 2011) and by the Karst Thrust (Bensi et al., 2009). The main effect of this thrusts system is the overlaying of the thick Cretaceous-Paleogene carbonate succession over the Eocene turbiditic one. The Palmanova Line connects the Dinaric thrust system of the eastern Friuli Plain to the Crni Kal Thrust in Slovenia and separates the External Dinarides from the *Istria-Friuli Underthrust Zone*, a separated deformed area being the boundary of the Africa-Apulia foreland (Placer et al., 2010).

In the Rosandra Valley, both the Dinaric structures and NE-SW or ENE-WSW oriented faults occur. They have played a crucial role in its geomorphological evolution. In particular, three main structures deeply conditioned its landscape: the

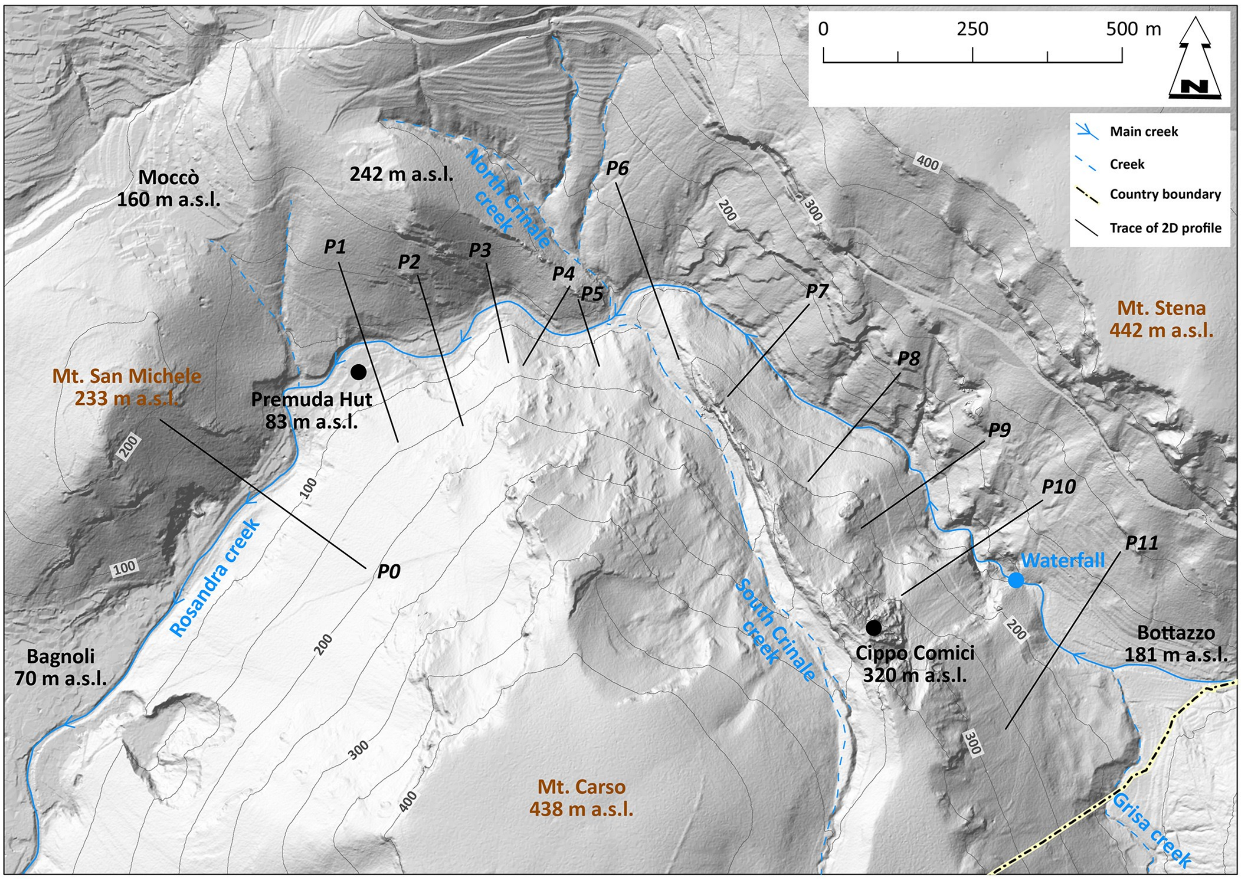

Fig. 2 - Hillshade of the study area realized through the processing of LiDAR data from Friuli Venezia Giulia Region. The profiles across the Rosandra Valley are numbered from 0 to 11.

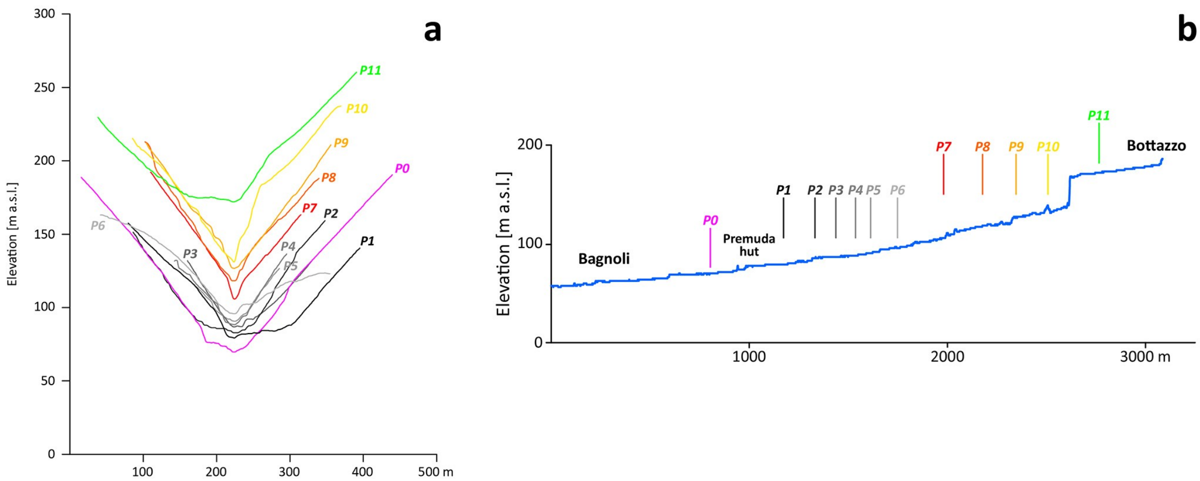

Fig. 3 - The profiles along the Rosandra creek: **a**) the overlapping of the profiles shows the uppermost one (green), near Bottazzo, 4 profiles in the gorge (yellow to red), and 6 profiles in the lower part of the creek (grey shades). The Profile 0 is out of the study area (magenta); **b**) longitudinal profile of the Rosandra creek.

thrust set located on the Mount Stena (Petrinje Thrust), the Crinale Thrust and the Socerb Thrust (Fig. 1b).

In the study area, three geological units, Eocene in age, occur: the Alveolinid-nummulitid Limestone (Early Eocene), composed by grey fossiliferous limestones; the Transitional Beds (Early Eocene, Burelli et al., 2008), constituted by an alternation of limestones and marls with a thickness of about 50 m; the Flysch, composed of alternated silty marlstones

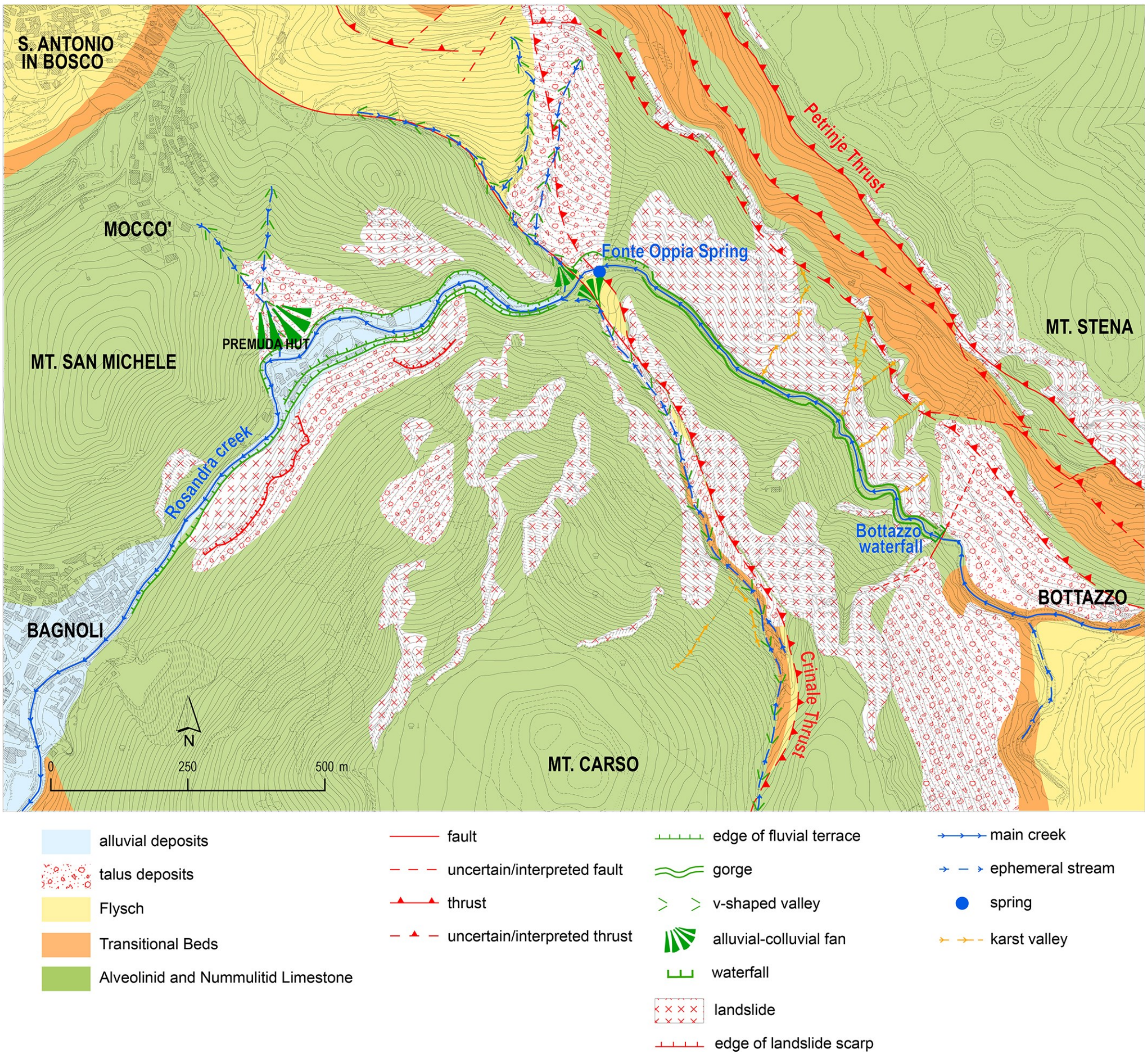

Fig. 4 - Geological map with geomorphological elements of the Rosandra creek and surroundings. The geological map is redrawn from Cucchi et al. (2013) and Jurkovšek et al. (2016).

and sandstones (Middle Eocene, Bensi et al., 2007).

The Rosandra creek, 15 km long, is the only surface stream in the Trieste karst area (Cucchi & Zini, 2008). The creek originates from the confluence of two small streams, Glinščica and Grisa. The springs are located in the Eocene Flysch area (Slovenia), then the creek crosses the Cenozoic limestones, within a 1 km-long narrow gorge and a subsequent wide sector with small terraces. At the valley outlet, the Rosandra creek forms a small floodplain up to the Gulf of Trieste (Fig. 1b). D'Amelio et al. (1997) measured a Q_{min} of 0.18 m^3/s and Q_{max} of 3.0 m^3/s, Q_{mean} ranging from 0.5-1 m^3/s. Discharge leaks occur along the stream, in particular along the carbonate sector, due to water sinking. Major increases after heavy rainfalls and minimum values during summer and winter droughts were measured (D'Amelio et al., 1997).

The annual average rainfall is 976 mm, while the average temperature is 15.0 °C and the relative humidity is 64%. Dominant winds come from the first quadrant (80 days/year), in particular Bora (ENE), which is more common during the cold season and can reach a maximum speed of 181 km/h, as measured in 1996 (Stravisi, 2008).

In the valley the human frequentation is documented since the Prehistory, with particular traces related to Bronze Age and historic periods. The remains of the Roman aqueduct are still partly preserved along the left side of the valley (Kocjančič, 2008).

3. METHODS

Geomorphological surveys were carried out in order to accurately map the extent of stream terraces. Field surveys were carried out during winters 2012 and 2015 in order to characterize the Quaternary outcrops.

The study area was surveyed by airborne laser scanning

Fig. 5 - Collage of images of the middle sector of the Rosandra Valley: a) alluvial/colluvial terrace at the confluence of the Rosandra with the South Crinale creek; b) the 28 m-high Rosandra waterfall near Bottazzo. It develops at the contact between Eocene Flysch and Tertiary limetones.

during March and April 2009 by the Protezione Civile of Friuli Venezia Giulia Region with a LiDAR system Optech ALTM 3033 (minimum point density of 4 points x m^2, relative horizontal and vertical accuracies are better than 1 and 0.3 m, respectively). LiDAR data, which are available in xyz format, were processed using ArcGIS 10.2 with 3D analyst tools. Digital terrain models (DTMs), with posting of 1m x px, were produced starting from the creation of TIN (Triangular Irregular Network) (Li & Heap, 2008).

The 3D analyst tools allowed to transform TIN into DTM, to sketch the longitudinal profile of the Rosandra creek and obtain the cross profiles of Rosandra Valley (Fig. 2, 3). The so-obtained 3D sections were converted in 2D through of an electronic sheet and AutoCAD Map 3D.

The sedimentological features of an unconsolidated Quaternary outcrop were described and sampled. Grain size gravel at 1 phi were measured using sieves, meanwhile frequency curves lower than 2 mm were determined using Malvern Mastersize Laser Diffraction at ½ phi.

Mineralogical analyses have been carried out by using a Siemens Stoe D500 diffractometer, CuKa radiation, monochromatized through a flat graphite crystal, in the range 2° - 50° 2 ϴ with a 0.01° step. Clay minerals have been separated through centrifugation and successively analyzed by XRD on oriented, glycholated and heated on glass slides in the range 2° - 50° 2 ϴ. Heavy minerals have been separated by means of tetrabromohetane (ρ = 2.96 g/cm^3) and successively identified at microscope and SEM. SEM images and qualitative chemical analyses have been obtained by using a Leica Stereoscan 430i EDS.

4. RESULTS

DTM analysis, field survey data and laboratory analysis are reported in the following paragraphs. Fieldwork was mainly devoted on the study of the outcrop near the Premuda Hut and the survey of the fluvial terrace which develops at the end of the gorge. The analysis of the relief and the stream profile have been developed. Moreover, the stratigraphic section of the outcrop was described and analyzed in detail.

4.1. Geomorphological analysis

The upper reach of the valley, where the creek flows on Flysch deposits, is characterized by low gradient (3.2%), up to the knickpoint, which corresponds to the Rosandra waterfall (28 m hight). The top of the waterfall is at an elevation of 166 m a.s.l., while its foot is at 138 m a.s.l. Downstream, the Rosandra creek enters in a gorge with an average gradient of 4.8% (Fig. 2, 3). The range in height of the gorge is from 138 m m.s.l. to 91 m m.s.l. This reach is characterized by incised meanders, from 1 m to 10 m large, potholes and other abrasion features, such as smooth surfaces, scallops, rapids, enclosed meanders and basins. After passing the gorge, the gradient is further reduced to about 2.6% (Fig. 3). In correspondence of the Crinale Thrust, about hundred meters after the end of the gorge (Fig. 2, 4), the creek gets the contribution of two small temporary tributaries, the South and North Crinale creeks (Fig. 5a). The first one forms a small alluvial fan with rounded sandstone blocks and cobbles in correspondence of the junction with the Rosandra. The surface of this fan is highly anthropic because it was interested by intensive farming up to the first years of the last century. The North

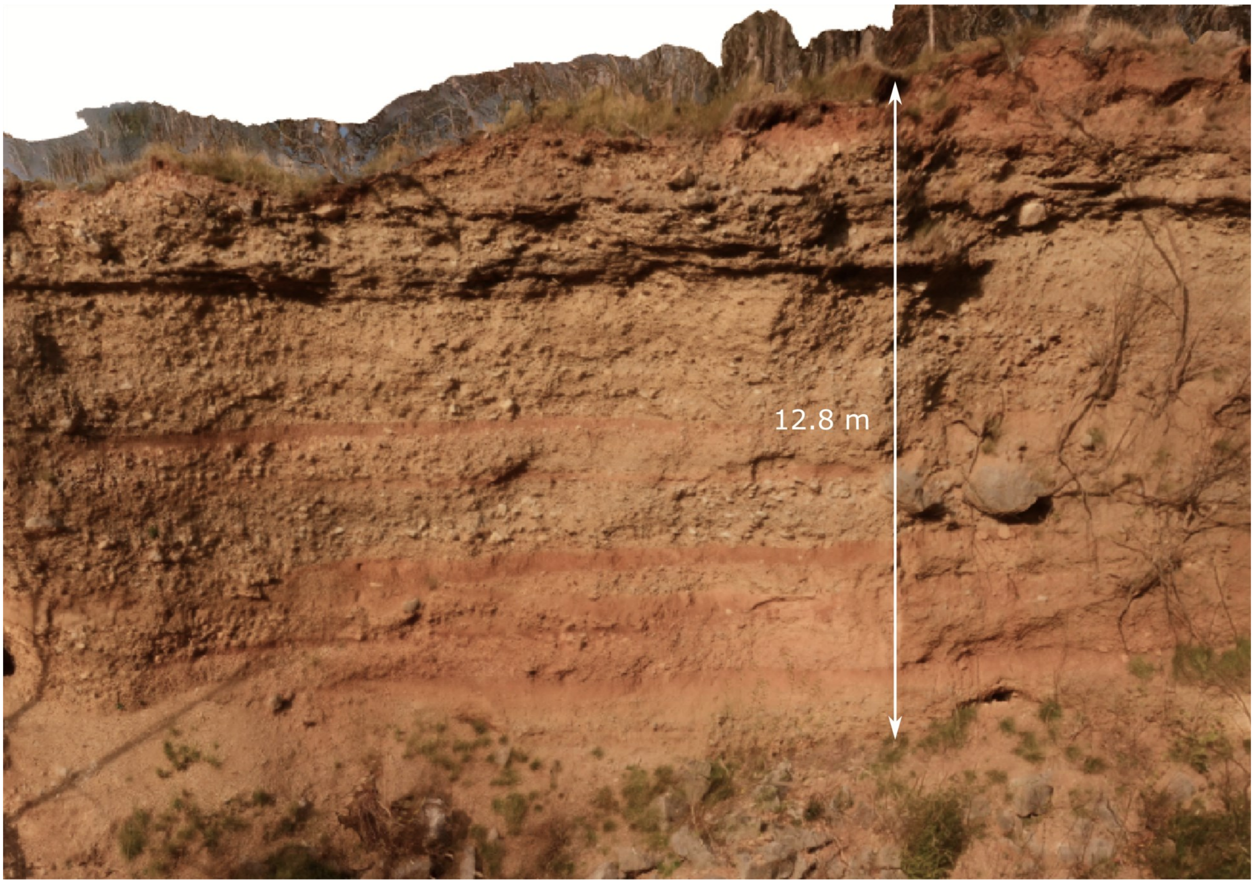

Fig. 6 - The stratigraphic sequence cropping out along the scarp of the terrace in front of the Premuda Hut (Bagnoli, Trieste).

Crinale creek erodes limestone debris up to the Rosandra, carrying limestone and sandstone blocks. Downstream of the Crinale Thrust, a poorly preserved stream terrace occurs along both the sides of the Rosandra creek roughly up to the Premuda Hut, where the valley becomes wider, up to about max 100 m. The terrace is composed by coalescing alluvial, colluvial with rockfalls and debrisfalls deposits. Sometimes it is incised by small gully-type channels. Toward the village of Bagnoli della Rosandra/Boljunec, several check dams were built across the stream in order to counteract erosion by further reducing the flow velocity.

The overlapping of the profiles shows that there is a significant difference in elevation a.s.l. from Profile 11 (Fig. 3, green) to Profile 10 (Fig. 3, yellow) and this is mainly related to the occurrence of the Rosandra waterfall (Fig. 5b). In correspondence of the Profile 11, the valley is very large. From Profile 10 to Profile 7, the valley is V-shaped in the upper part, while the lower part is dominated by a gorge, which deepens the valley at its bottom. In this sector, the valley slopes are interested by steep limestone cliffs alternating flat banks (northern slope of the creek, Profiles 9 to 10, southern slope of the creek, Profile 7 to 9). From Profile 6, the Rosandra Valley widens and alluvial terraces occur on the left side of the stream (Profile 6 to Profile 1), but also on the right side (Profile 5 to Profile 2). Two orders of terraces are recognizable on the left side of the Rosandra creek in this sector, while on the right side limestone beds occur. The upper terrace is well-defined in the Profiles 6 to 2. Two orders of terraces are recognizable in correspondence of Profile 1, while in Profile 0 it is in the opposite side of the stream (Fig. 3).

4.2. Sedimentology

The sedimentological analysis was carried out in correspondence of the highest and better preserved sector of the terrace. The most complete unconsolidated sediment outcrop occurs along the right bank of Rosandra creek, just in front of the Premuda Hut (Fig. 4, 6). It extends in length for about 100 m and has a maximum height of more than 12.8 m (Fig. 6). The studied section is composed by a number of alternating gravelly and fine-grained levels. Nine samples (A to H3, Fig. 7) were collected to determine the sedimentological and mineralogical characteristics of the sequence and to define the related sedimentary processes and the paleoenvironmental setting. The graphic results of sedimentological and mineralogical analysis are reported in Fig. 7 and Fig. 8.

Most of the sequence is characterized by alluvial levels, which reflect different energy environments. Alluvial levels, decimetric to metric in thickness, are characterized by high percentage of gravel (80-40 %) together with rounded and sub-rounded sandstone clasts (Fig. 6). The fraction finer than 2 mm is poorly classed or sometimes bimodal in size.

The Level 3.1 (Sample F) is composed mainly by muddy gravels with sub-angular limestone clasts with modal size of 8-16 mm.

Gravelly levels are interbedded with thin (up to 0.6 m) fine-grained beds, which are more frequent in the lower part of the sequence. One of these layers (Level 6, sample D, Fig. 7) is made of coarse silt with very fine sand, well-sorted with very high percentage of quartz (93%). Some blocks, up to 1 meter in size, are included in Level 7 and are related to gravitational processes and landslides.

The sedimentary succession can be interpreted as the interfingering of alluvial, colluvial or rockfalls and debrisfalls deposits (*sensu* Blikra & Nemec, 1998).

Radiocarbon datings from the Level 2 indicates that the deposit is older than 45.000 Years BP (Sample: LTL12727A, Radiocarbon Age BP: >45.000 years, δ^{13} C (‰): -21.3±0.7).

The succession can be roughly divided in three units (Fig. 8):

I) the basal unit, at the cliff toe (Levels 1 and 2), which is made of medium and high-energy alluvial levels;
II) the middle unit (Level 3 to 7), which is characterized by fine-grained sediments, talus deposits (originated by debris and rockfalls) and, to a lesser extent, alluvial deposits;
III) the upper unit of the sequence is again composed by coarse alluvial sediments of high-energy flow.

4.3. Mineralogy

The studied samples consist of calcite, quartz and feldspars. According to the percentages calculated using the intensities of the highest peak of each phases, layers 3, 11 and 12 (Sample A, B, F) display a major amount of calcite (40-60%), while layers 3.3, 6 and 8 (Samples C, D, E) are characterized by the highest quartz content (>80%). In the layers 1.2 and 2 (sample G, H3 and H), the quartz content is between 70 and 80%. Feldspars content is always below 5% (Fig. 8).

The analysis of clays shows that all the samples are very similar. Among the clay minerals, montmorillonite and illite-montmorillonite mixed-layers suggest they are residual clays of neo-formation, as suggested also by Lenaz et al. (2004).

The heavy mineral assemblage was studied on selected layers, in particular Levels 2, 3, 6 and 7 (Samples C, D, E and G). The amount of heavy minerals is quite scarce and among the different minerals, garnet and zircon (sometimes euhedral, Fig. 10) are the most abundant. Chromite, magnetite, sulphides, tourmaline and rutile have been also found. In the layer 6 one single occurrence of a pale blue crystal have been found. According to the qualitative chemical analyses performed via SEM it is an aluminum silicates (kyanite or sillimanite).

5. DISCUSSION AND CONCLUSIONS

The new data collected along the Rosandra creek show the complexity of the tectonic and geomorphic setting of the valley, but they yield also significant information to study its

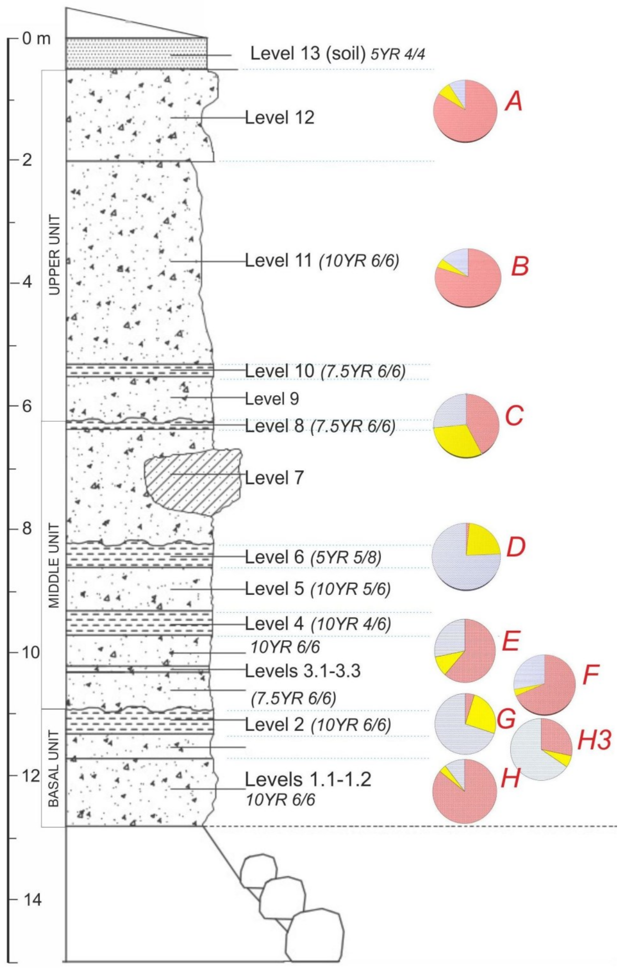

Fig. 7 - Stratigraphic description of the Premuda sequence. The circle diagrams show the percentage of gravel (red), sand (yellow) and mud (blue).

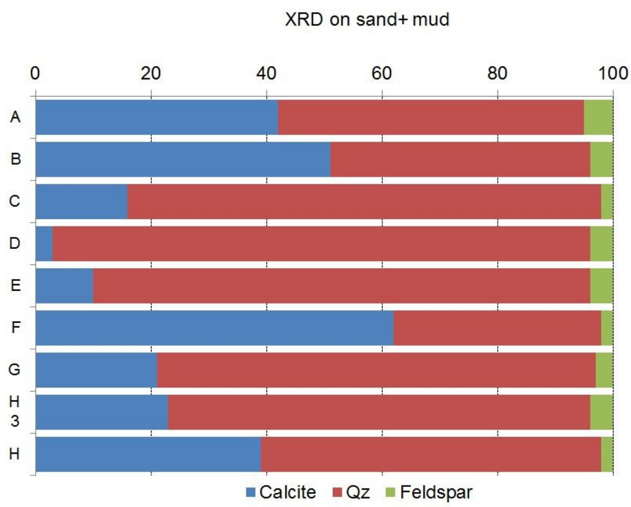

Fig. 8 - Percentages of calcite, quartz and feldspars in the studied layers by means of XRD.

Quaternary evolution.

The middle reach of the Rosandra creek develops in correspondence to main tectonic structures. The Crinale Thrust is the most important and dissects the valley, producing a diversion in the flow direction from NW to SW (Fig. 2, 4). Lithology also plays an important role in its evolution. The upper part of the stream develops in Eocene Flysch, the middle part is cut in limestones while the lower part flows in the floodplain. The contact between the Flysch Formation and limestones is characterized by a knickpoint (28 m high), which develops along a fault plane (Fig. 4). Abrasional features on the top of the waterfall indicate that the knickpoint is currently eroding upstream (Fig. 5b). Downstream, Rosandra creek flows into the limestone gorge. Here, the hillsides become steeper, with structural terraces along the right slopes (Fig. 3, Profile 10) and the presence of landslides (Paronuzzi et al., 2016). In this sector, a deep canyon-like depression dominated by abrasional landforms occurs. The gradient is the highest in the study area, about 4.8%. This sector is characterized by almost complete absence of deposits except for some limestone cobbles or small blocks fallen from the slopes. Moreover, the waterfall acts as a selective dam, because only fine sediments flow downstream. At the end of the gorge, the gradient becomes considerably lower, 2.6%, and the waterflow speed is significantly reduced (Profile 6). Two ephemeral tributaries, the first from the South and the second from the North follow the Crinale Thrust and flow into the valley roughly at the end of the gorge. The southern one created an alluvial fan mostly made of rounded sandstone blocks and cobbles (Fig. 5a). Downstream, a partially eroded stream terrace occurs along both the sides of the Rosandra creek roughly up to the Premuda Hut. The downstream continuity of the terrace is clear along both sides of the creek. Colluvium is made of clastic slope-waste materials, coarse grained and angular, deposited at the foot of the hillslopes, mainly transported by sediment-gravity processes (Holmes, 1965). The lower part of the terrace is mainly made by rounded or sub-rounded sandstone blocks and cobbles in a fine matrix. A survey along the Rosandra stream highlighted the absence of sandstone clasts in the sector between the waterfall and the end of the gorge, suggesting the mixed contribution of the aforementioned tributaries and the Rosandra to the sedimentation of the terraces. On the contrary, during modern floods, Rosandra creek carries large amount of suspended fine sediments from the upper sector of the flysch basin.

In correspondence of the Premuda Hut, the valley is larger than other reaches, so the preserved terrace is relatively wide. In front of the hut, the scarp of the terrace is about 12 m high and shows a stratigraphic succession. It represents the largest Quaternary exposed deposit in the Trieste area, except for cave deposits (Andreolotti, 1965, 1966; Belloni & Orombelli, 1972; Falguares et al., 2008; Boschian, 1998; Boschian & Desantis, 2011).

^{14}C age on a frustule plant collected in the lower part of the deposit indicates that the age of the sample is older than 45.000 yrs. BP. The plant remain can hardly be reworked because the upstream narrow and steep topography of the valley prevent sedimentation. Hence, the age of the lower part of the succession could be also older than Late Pleistocene. The sedimentation of the sequence may have been also very fast, as testified by late Holocene sequences in western Istria (Faivre et al., 2011; Felja et al., 2015).

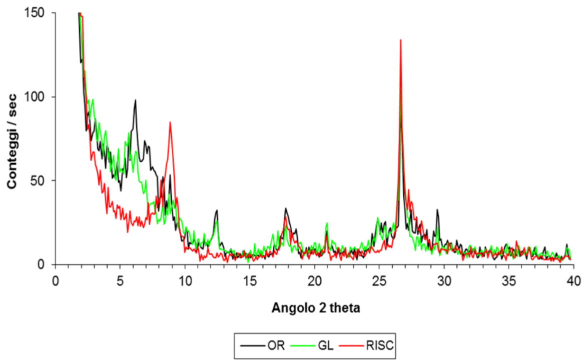

Fig. 9 - XRD of clay fraction on oriented, glycholated and heated glass slides.

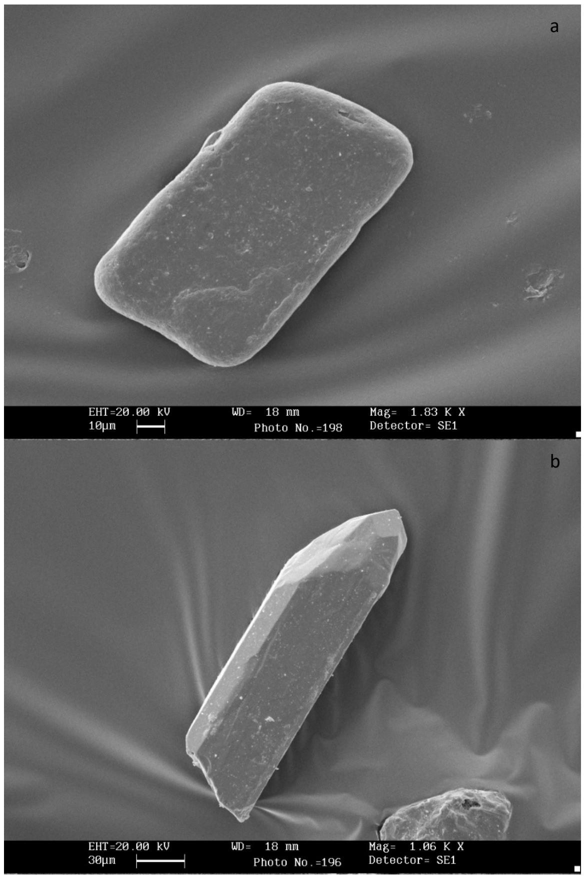

Fig. 10 - a) aluminum silicate in layer E; b) zircon in layer C.

The composition of sample C, D and E is similar to the composition of *terra rossa* soils in the Trieste Karst area (Lenaz et al., 1996), which are mainly constituted by quartz (about 90%), feldspars and clay minerals, while calcite is absent. Other layers of the studied sequence are enriched in calcite suggesting local provenance by gravity processes from hillslopes.

According to Chiesa (1972), Šinkovec (1974) and Lenaz et al. (1996), accessory minerals in sandy fraction of karst soils are rutile, tourmaline, garnet, Cr-spinel, corundum, hematite and limonite, zircon and phyllosilicates as biotite and muscovite. Several authors (Malaroda, 1947; Wiesender, 1960; Woletz, 1960; Crnjakovic, 1994; Lenaz et al., 1996; Lenaz et al., 2000) suggested, by comparing the mineralogy of *terra rossa* and that of the surrounding silicoclastic formations, that *terra rossa* is the result of flysch weathering. The mineralogy of the here studied samples is very similar to that of the already studied karst soils and of the flysch so that an analogue source should be considered. The solely occurrence of one aluminium silicate could suggest that another supply, maybe reworked by aeolian processes, could be also present.

Regarding the evolution of the Rosandra valley, the geomorphological and sedimentological reconstruction suggests the interaction between the floods, related to very rainy periods, and the constrain provided by the narrow riverbed affected by debrisfalls and rockfalls coming from the hillslopes. In correspondence of the Premuda Hut, the Rosandra Valley widens up to about 100 m allowing the preservation of ancient alluvial successions, as testified by alternations of fine and coarse units topped by the debris fan from Moccò.

Also the tectonic setting of the area may have influenced the shaping of the valley. Many authors highlighted the occurrence of a SE-NW tilting of the Karst plateau, from Trieste to the northern sector of the gulf (Antonioli et al., 2004, 2007; Furlani et al., 2011; Carulli, 2011; Melis et al., 2012; Biolchi et al., 2016), using geomorphological, sedimentological, archaeological and geophysical data. These studies indicated that the city of Trieste is tectonically stable, while the coast subsided moving toward NW and, according to Braitenberg et al. (2005) the tilting is still active. Cox (1994) suggested that streams that flow in the direction of tilting produce steepened gradients, such as the aforementioned sector of Rosandra interested by the gorge, which flows towards NW, following the direction of the tilting. Comparing the topographical trend of the Karst plateau (Fig. 1c), we suggest that the Rosandra Valley could represent the south-eastern prosecution of the tilting. The rejuvenation of the Rosandra creek, together with the subsequent stream downcuts, could be related to the uplift of the Rosandra Valley, SE limit of the tilted area. Moreover, the contribution of late Quaternary sea level changes could also have enhanced the incision of the valley. The geomorphic regime changed to erosion, as recorded by fanhead trenching and cutting of fluvial terraces, and it persists until present, as highlighted by small terraces incised in Flysch along the North Crinale creek. Now, Rosandra and tributaries do not provide coarse sediments like the ones found in the deposits. During present-day floodings, only fine material is carried out and the waterfall acts as a natural dam for sandstone blocks from Flysch. Therefore, the incision of the gorge may have been accelerated during rainy periods, as suggested by Furlani et al. (2009) in high energy environments, when large amount of flysch materials provided abrasion tools that increased erosion rates, maybe of one or two orders of magnitude.

ACKNOWLEDGEMENTS

We are very grateful to Dr. Elia Zordan for field surveys and to *Protezione Civile* of Regione Autonoma Friuli Venezia Giulia for LiDAR data. Moreover, we thank Mr. Mauro Bussi, University of Trieste, for sedimentological analysis.

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Ms. received: February 5, 2016
Final text received: June 28, 2016