



## Abstract

A landslide, to the west of Montemurro (a small village in Southern Italy), has recently caused damage to buildings and other infrastructures in an urbanized area, as a result the development of new economic activities has been prohibited. The landslide was discovered in the last century and has been studied since the 1990's using classical geotechnical methods, but the sliding body continues to move. In this paper, we will present the results of a study carried out using field surveys, geognostic investigations and TDR (Time Domain Reflectometry) measurements in order to reconstruct the stratigraphy of the sediments involved and to further understand the geological and geomorphological context of the slope. This study is part of a larger multidisciplinary project of which the results will also be presented in this paper. The landslide (rotational slide in the upper sector, developing into a translational slide in the lower part) affects Quaternary continental clastic deposits resting on a bedrock formed by Tertiary siliciclastic sediments of the Gorgoglione Flysch. TDR measurements did not show any significant movement during the period monitored (January 2013–January 2014). Slip zone geometries were hypothesized using inclinometric measurements taken from previous studies, stratigraphic data and geomorphological interpretations of topographic scarps. Feedback from monitoring will confirm this hypothesis.

## 1 Introduction

Landslides in urbanized environments can cause serious socio-economic damage and loss of human life. As a result, scientific interest has increased and has focused on supporting technical studies using integrated methodologies, traditional and innovative techniques and a scientific approach.

Our attention has been focused on a pilot area in the Agri Valley, Basilicata, Southern Italy, on the left orographic side of the Agri river. The landslide studied affects a slope to the west of Montemurro town. This is a semi-urbanized environment where several

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anthropic buildings have suffered significant structural damage: old farmhouses with evidence of reactivated movements over time; collapsed old dry stone walls; cracked natural spring fountains; and other fractured stone or masonry constructions. Roads, retaining walls and a tunnel were also damaged, creating traffic problems and public inconvenience. All resulting in an increased interest in this landslide over the last few years.

Despite numerous studies during the last century, the complex geological and geomorphological framework of the area means the causes of movement affecting the slope and the slip depth are not yet fully constrained. Further investigations were carried out in order to better understand geological context and geomorphological landslide characters, to reconstruct the stratigraphy of the soils in detail and to identify the slip zone(s) and their relative depth.

**2 Methodologies**

A detailed geological survey was performed, considering the landslide area and the surrounding slope sectors. Geomorphological analysis was carried out using field surveys and stereoscopic observations of aerial photographs from Istituto Geografico Militare (IGM). Two series of photographs were used: (1) late summer 1985, 1/31 000 scale, acquisition height 5330 m, (2) spring 2003, 1/30 000 scale, acquisition height 5000 m.

Two geognostic boreholes (R1, 47.5 m and R2, 40 m) were drilled in order to reconstruct the stratigraphy of the deposits involved. A pre-existing geognostic borehole (S1), equipped with an inclinometer tube, provided indications of a slip zone, as reported by Summa et al. (2014). However, the break of the inclinometer tube did not allow for further monitoring. As a result, boreholes R1 and R2 were also equipped with TDR (Time Domain Reflectometry) sensors, in order to further evaluate depth and sliding geometry, identify any deeper slip zones and monitor the whole movement.

Over a hydrogeological year, groundwater level fluctuations were determined. Two measurements were taken, September 2012 and May 2013, and were considered to be representative of maximum and minimum aquifer recharge. The measurements were performed in boreholes R1 and R2 piezometers, in other pre-existing geognostic boreholes and in all available water wells, providing the best possible distribution of the measuring points over the study area.

### 3 Geological setting

#### 3.1 The Agri Valley Basin

The Agri Valley Basin is an inter-mountain basin belonging to the axial sector of the Southern Apennines (Fig. 1), an east-verging fold-and-thrust belt developing as an accretionary wedge from Late Oligocene to Early Pleistocene due to the eastward migration of the apenninic arc (e.g. Doglioni et al., 1996; Gueguen et al., 1997, 1998; Pescatore et al., 1999; Parotto and Praturlon, 2004; Novellino et al., 2012; Bucci et al., 2014).

Lucanian Apennines tectono-stratigraphic units are derived from the Afro-Adriatic paleomargin deformation and are tectonically layered as follows: the Liguria-Piedmont ocean units of the Liguride and Sicilide Complex, from Cretaceous to Oligocene; Apennine Platform carbonate units, from Late Triassic to Tertiary; the Lagonegro Basin units, from Late Paleozoic to Tertiary (e.g. Scandone, 1967; Ogniben, 1969; D'Argenio et al., 1975; Mostardini and Merlini, 1986; Carbone et al., 1991; Roure et al., 1991; Monaco et al., 1998; Cello et al., 2000a; Menardi Noguera and Rea, 2000; Lentini et al., 2002; Tavarnelli and Prosser, 2003; Piedilato and Prosser, 2005). Thrust sheet top silico-clastic deposits (e.g. Gorgoglione Flysch) are emplaced by Tertiary upon tectonostratigraphic units indicated above (Carbone et al., 1991; Butler and Tavarnelli, 2006 and references therein).

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Alloformation, Valle del Nasillo Alloformation, Vallone dell'Aspro Alloformation and Torrente Casale Alloformation. This sequence reflects a progradation of fan systems in a lacustrine-palustrine setting, followed by expansion of a new alluvial-fluvial system (Zembo, 2010).

5 Carbone et al. (2010) recognized a Pietra del Pertusillo Supersynthem on an unconformity-bounded stratigraphic unit including the Breccie di Galaino and the Conglomerati di La Serra (sensu Salvador, 1987), corresponding to the Spinoso Conglomerate Formation of Zembo (2010). The Pietra del Pertusillo Supersynthem is composed of three synthems (Grumento, Bosco dell'Aspro and Bosco San Lorenzo from bottom  
10 to top), representative of coeval fluvial plain, alluvial fan and lacustrine deposits and matches the Agri Valley Allogroup of Zembo (2010) and the Complesso Val d'Agri of Di Niro et al. (1992), Di Niro and Giano (1995) and Boenzi et al. (2004).

In the Agri Valley Basin, from Pleistocene to Olocene, Giano (2011) recognized five generations of slope and alluvial fan systems, consisting of coarse-grained slope and  
15 alluvial deposits with reddish paleosols interbedded with, or on top of, the sedimentary fans. The oldest fan system corresponds to the Spinoso Conglomerate Formation of Zembo (2010) and to the unconformity-bounded stratigraphic unit in which Carbone et al. (2010) included the Breccie di Galaino and the Conglomerati di La Serra, while the subsequent fan systems can be related to the Agri Valley Allogroup deposits of  
20 Zembo (2010) and the Pietra del Pertusillo Supersynthem of Carbone et al. (2010).

#### 4 New geological framework from field surveys

The field surveys carried out during this work define a detailed geological setting of the study area and recognize the reciprocal stratigraphic or tectonic contacts between the different outcropping formations, as shown in the sketch map and sketch section in  
25 Fig. 3.

In the area studied, mainly continental clastic Quaternary deposits of slope, alluvial and lacustrine environments outcrop. These deposits rest on a bedrock formed by the

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Tertiary siliciclastic sediments of the Gorgoglione Flysch, observed in several outcrops distributed mainly upstream from the village of Montemurro, and in the more engraved ditches.

The Gorgoglione Flysch formed from Middle Langhian to Lower Tortonian in a piggy-back trough during the Apennine orogeny compressional deformation phase producing the Irpinian Basin (Boenzi and Ciaranfi, 1970; Ciaranfi, 1972; Colella, 1979; Lentini et al., 1987; Carbone et al., 1988; Loiacono, 1993; Boiano, 1997; Butler and Tavar-nelli, 2006). It is composed of three sequences of terrigenous sediments (arenaceous and arenaceous-conglomeratic; arenaceous-marly; silty-arenaceous-marly), interbedded and repeated several times at different stratigraphic heights, marking several pulsating torbiditic events (Boenziet al., 1968; Boenzi and Ciaranfi, 1970; Critelli and Loiacono, 1988; Mutti and Normark, 1987). In the area studied the pelitic-arenaceous sequence prevails. The main outcrops are upstream from the village of Montemurro, close to the San Vito Pass, and along a large section extending from the village's cemetery to the Scannamogliera stream. Other outcrops affect all the incisions of this stream, up to the confluence of the Notarmario ditch, where one of the best exposures can be seen (outcrop O1, Fig. 4a). The northern part of the village is also located on the Gorgoglione Flysch, with several buildings directly resting on massive sandstones (outcrop O2, Fig. 4b). The pelitic-arenaceous sequence, exposed in these outcrops, is mainly composed of grey, yellowish or whitish quartz-feldspar sandstones, with grey or brown silty marls and interbedded silty clays. The decimetric to metric sandstone banks often show yellow ochre surfaces altered with whitish veins, carbonatic cement-filled, and a graded vertical bedding characterized by breccias with millimeter and centimeter pebbles at the base. These basal breccias rest on the underlying pelitic level with a very sharp contact, while the transition upward to the finer upper level is more gradual (outcrop O3, Fig. 5).

An isolated outcrop representative of the arenaceous-marly sequence is located on the right orographic side of the Scazzera ditch, SW of the village of Montemurro. It is characterized by grey and whitish marls, silty marls and marly clays, strongly interbed-

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ded and fragmented in slivers and scraps, due to intense tectonic deformation (outcrop O4, Fig. 6).

In the study area the continental clastic Quaternary sequence rests on an angular unconformity truncating the Miocene bedrock, as shown in the geological sketch section in Fig. 3. It is represented by alluvial fan, alluvial plain and lacustrine deposits corresponding to the middle and upper intervals of the Complesso Val d'Agri of Di Niro et al. (1992) and to the Vallone dell'Aspro and Torrente Casale alloformations of Zembo (2010).

Most of the Pleistocene deposits affecting the study area can be attributed to the Vallone dell'Aspro Alloformation, characterized by coarse to fine sands and stratigraphically lower greenish to grey silty clay and clayey silts, interbedded with organic-rich peaty levels. Both upward and downward, along the stratigraphic sequence, clast-supported coarse conglomerates and sandy gravels can be observed. The upper conglomerates show imbricated pebbles of different composition, mainly arenaceous and subordinately siliceous and igneous, while the composition of the lower gravels, often characterized by a reddish sandy matrix, is mainly dolomitic, calcitic, siliceous and arenaceous, with rarer clasts of varicoloured argillites and metamorphic rocks (Zembo, 2010). This alloformation corresponds to an axial braided alluvial system where the water and sediment supply was both from main stream and transverse alluvial fans. This environment was also characterized by outcast refilled channels, pools and ponds, temporary lacustrine-palustrine settings associated to flood events, interfluves areas, as shown by the accumulation of mollusks typical of open vegetated zones, organic layers representative of standing swamp area and flash flood laminated structures (Beraldi-Campesi et al., 2006; Pisegna Cerone, 2008; Zembo, 2010).

The Vallone dell'Aspro Alloformation's most representative outcrop is on an artificial scarp along the SP11 road, at 580 m a.s.l., in the Dell'Avena Bridge area, on the right orographic side of a small incision tributary of the Scannamogliera stream (outcrop O5, Fig. 7). This artificial scarp was excavated during the construction of a new road and allowed the observation of a freshly exposed sandy and clayey deposits outcropping in

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millimeter to centimeter clasts, and as yellow ochre sands. The same characters can be recognized in other outcrops in the study area.

The contact between the Torrente Casale and Vallone dell'Aspro Alloformation deposits is a composite surface, erosional in the north and depositional towards the basin, based upon a weathering profile composed of a fersiallitic/brunified pedocomplex with two paleosols corresponding to two erosion episodes (Zembo, 2010). In the study area, this surface can be observed, though laterally discontinuous, at about 650 m a.s.l., at the top of the vertical walls on the left orographic side of the Scazzera stream, and shows a moderate rubrification due to iron and manganese oxides and hydroxides.

The Quaternary continental deposits, that stratigraphically overly the Miocene bedrock in onlap relationship, are plan-parallel, arranged in subhorizontal to gently south-dipping strata towards the basin depocenter.

## 5 Geomorphological setting

Results of the geomorphological analysis carried out in the area studied are reported in the geomorphological sketch map shown in Fig. 9.

The western side of the village of Montemurro is characterized by an obvious slope change controlled by the different competence of the outcropping lithologies. The presence of alternating turbidite sandstones, siltstones and silty clays in the northern sector produces steeper slopes as opposed to the southern sector where Quaternary deposits, consisting of conglomerates, sands and clays occur. The area is characterized by a diffuse geomorphological instability involving the entire slope from the Scazzera stream, 810 to 590 m a.s.l. and 1500 m in length.

Landslides affect mainly Quaternary continental deposits of the Val d'Agri Basin and also, in the topmost slope sector, the Gorgoglione Flysch sandstones. In some cases, it is possible to recognize landslide main scarps, minor scarps, terrace-like features and counter-slopes, particularly pronounced along the southern sector of the slope.

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Geomorphological trenches in the foothills of fault scarps and landslide niches have also been observed.

An impressive pre-1954 quiescent landslide involves the entire area delimited by the road from Montemurro town to the cemetery to the north, by the Montemurro high to the east, by the conoid southwestward of the cemetery to the west and by the Scazzera ditch to the south. The damaged area is about 40 ha and subsoil geological structures have been completely reworked and altered. The entire area is still active and has been affected by many smaller landslides events.

Now, the main landslide activity affects the slope in the Verdesca area, where significant evidence for on-going activity has been observed; this consists of structural damage to infrastructure and anthropic buildings (e.g., dislocation of SP11 road tunnel box, warping of retaining walls, deformation of road embankments, road surfaces and old manmade structures (Fig. 10) (Bentivenga et al., 2012).

The area is affected by a complex landslide, about 700 m long and 325 m wide, developed between 675 and 590 m a.s.l., with a maximum elevation difference of about 85 m between the upper and the lower portions of the landslide body. The size of the damaged area is about 20 ha. The landslide body steepness in the accumulation area is about 14°, while it is about 12° in the source area.

In the upper sector this landslide is a rotational slide, evolving, in the lower part, into a translational slide (Varnes, 1978; Cruden and Varnes, 1996). The landslide foot has been affected by further superficial movements, due to the continuous erosion of the Scazzera stream, whose course is diverted in relation to the zone accumulation. Inside the landslide, in relation to minor scarps, two piezometric surfacing springs were identified.

## 6 Stratigraphies and geognostic investigations

The main features of the stratigraphic logs reconstructed along the R1 and R2 boreholes are shown in Fig. 11.

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The first sediments found were attributed to eluvio-colluvial and detritic deposits, with thickness increasing downstream up to a maximum of 14 m in borehole R2. Below these deposits, sandy-silty sediments were observed, with a clayey component strongly varying with depth. The predominant yellow-ochre coloring is due to the high weathering rate, favored by the significant deconstruction of the sediments and the groundwater circulation. In the borehole, the coarser silty-sandy sediments switch to clayey silts, with several interbedded blackish peaty levels, at several stratigraphic depths. This transition shows a deepening downstream, dropping from 16 to 20.5 m below ground level. Silty levels affected by dark nodules and blackish saline concretions can also be observed, respectively due to oxidation phenomena and solution-precipitation processes favored by groundwater circulation. These stratigraphic logs are consistent with that of the S1 borehole, described by Summa et al. (2014). The clastic component increases with depth, anticipating the appearance of sandstone strata at about 40 m deep in borehole R1.

From a hydrogeological point of view, groundwater is consistently close to ground level, and fluctuations of a few centimeters were identified between the periods of maximum and minimum aquifer recharge. The anomalously higher values of the groundwater level in the central sector of the area studied is probably linked to engineering draining actions carried out in the past along the provincial road. The isopiezometric maps are shown in Fig. 12.

TDR measurements were carried out every two months from January 2013 until January 2014, using a Megger 2000 instrument and a RG-58 rigid coaxial cable for deformation measurements with a tinned copper inner conductor (50 ohm) and PVC jacket installed in both R1 and R2 boreholes. Instrumental accuracy was 0.1 % of range. However no significant movement was detected.

## 7 Discussion and conclusions

Field surveys and stratigraphic interpretations of geognostic boreholes enabled the definition of a detailed geological, geomorphological and hydrogeological framework of the study area, to understand some important features of the landslide and to reconstruct the trend of the slip zone.

The slope studied is affected by a strong Quaternary morphodynamic, with several sequential events involving the Miocene siliciclastic deposits of the Gorgoglione Flysch, that represent the pre-Quaternary bedrock, and Quaternary clastic sediments of the Agri Valley Allogroup (Torrente Casale and Vallone dell'Aspro Alloformation).

A more significant outcrop of the Vallone dell'Aspro Alloformation in the area studied shows a sequence of sandy and silty sediments resting on clayey silts, with a blackish peaty level. The investigated sequence is consistent with that reconstructed along boreholes R1 and R2: from this analogy, it is possible to ascribe the sediments affected by the landslide studied, in total or partly, to the finer facies of the Vallone dell'Aspro Alloformation. These sediments can be considered saturated during the entire hydrogeological year, principally in relation to the areas showing more significant evidence of instability, such as that of the road tunnel (Verdesca area).

The Verdesca landslide is complex, characterized by a rotational slip evolving downstream into a translational slip. Recent movements involving a road tunnel, retaining walls and other manmade structures, cracked an inclinometer tube in a pre-existing borehole at 14.3 m depth located near the road tunnel, allowing for the identification of a slip zone at that depth (Summa et al., 2014).

We reported in the geomorphological profile A–A' (Fig. 13) the trend of the hypothesized slip zones, considering both lithological transition (also easily identified in boreholes R1 and R2 at a depth ranging between 16 and 20.5 m below ground level), and the geomorphological interpretation of topographic scarps.

Only further TDR measurements will make it possible for us to confirm or modify the hypothesized slip zone geometries, as no significant movements were detected

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in the monitored period (January 2013–January 2014). In this phase, pending direct feedback from TDR monitoring, geomorphological reconstruction of the slip zones and stratigraphic interpretations of geognostic holes have been valuable support tools in defining the slip of the landslide studied and to plan technical interventions aimed at mitigating risk and preserving existing manmade structures.

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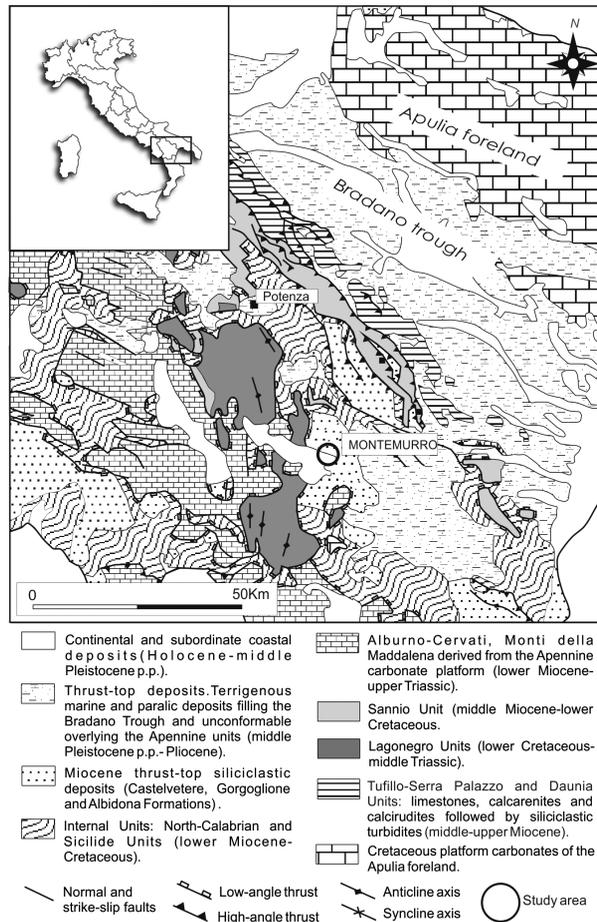


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**Figure 1.** Geological sketch map of the Lucanian Apennine with the site of the study area (from Patacca and Scandone, 2007, modified).

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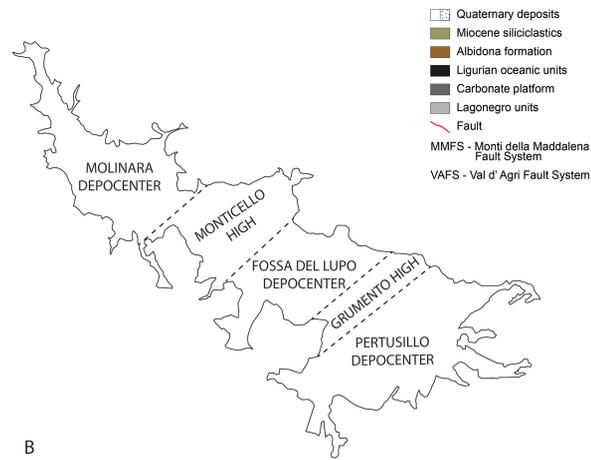
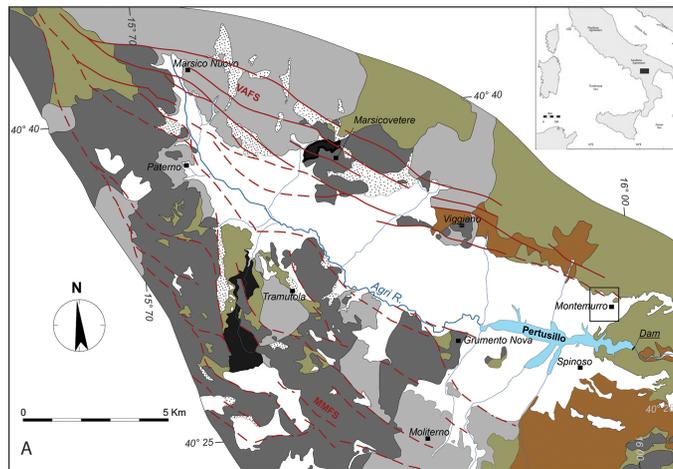
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**Figure 2.** Geological sketch map of the Val d'Agri Basin (modified from Giocoli et al., 2015).

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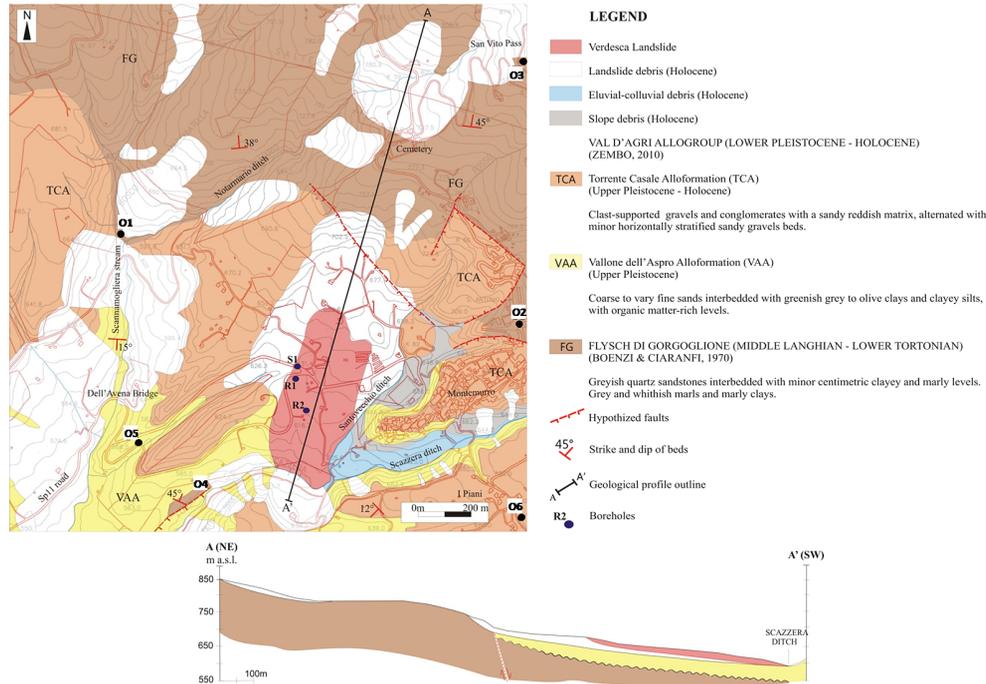
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**Figure 3.** Geological sketch map and geological section (A–A') of the study area.

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**Figure 5.** Outcrop of the Gorgoglione Flysch pelitic-arenaceous sequence at the San Vito Pass. Grey or yellowish sandstones and grey or brown silty marls and silty clays are interbedded. In the zoom box **(a)** the very sharp contact between sandstones and the underlying pelitic level is shown.

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**Figure 6.** Exposure of the Gorgoglione Flysch arenaceous-marly sequence. Grey and whitish marls, silty marls and marly clays, strongly fragmented in slivers and scraps.

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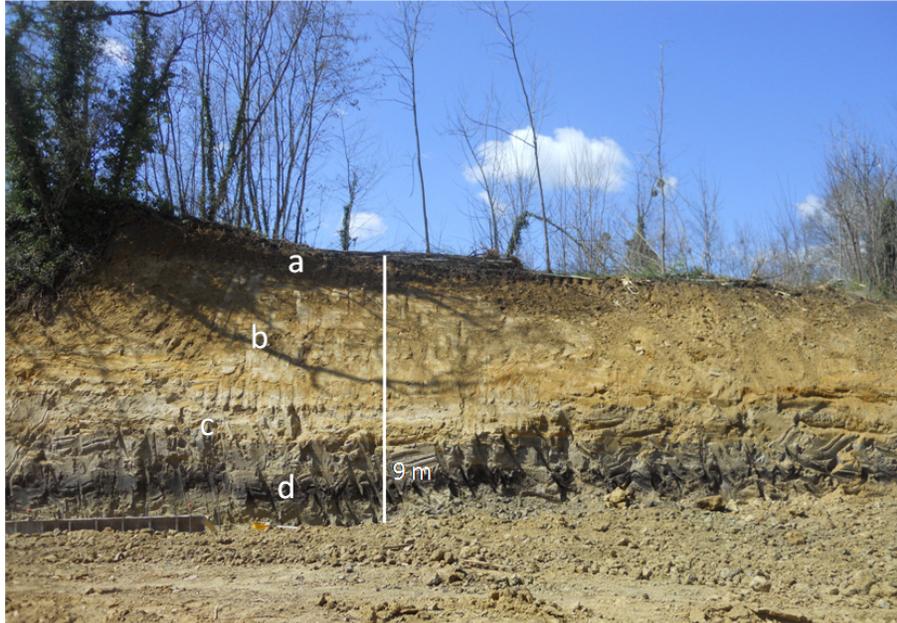
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**Figure 7.** Artificial scarp along the SP11 road, with a representative exposure of the Vallone dell’Aspro deposits. Below a meter-thick soil **(a)** there are pebbly sands **(b)** and grey clayey silts **(c)**. A very dark 40cm-thick peaty level, organic matter-rich, can be observed near the base of the outcrop **(d)**.

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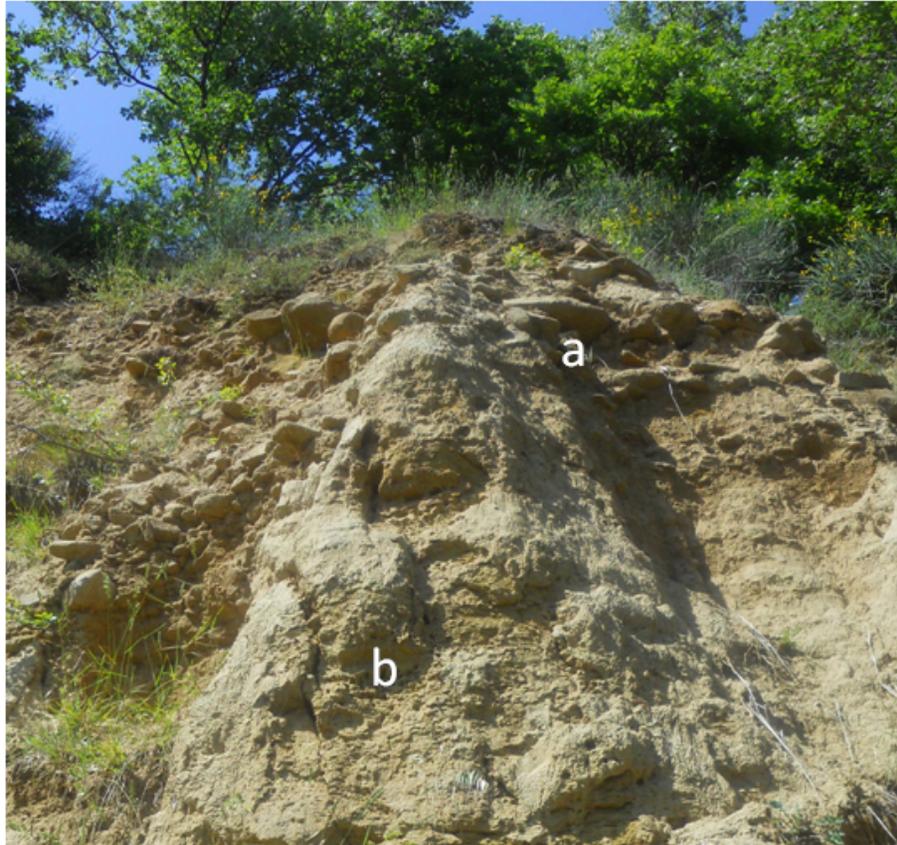
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**Figure 8.** Representative outcrop of the Torrente Casale Alloformation. Clast-supported massive conglomerates **(a)** upon sandy gravels and gravelly sands **(b)**.

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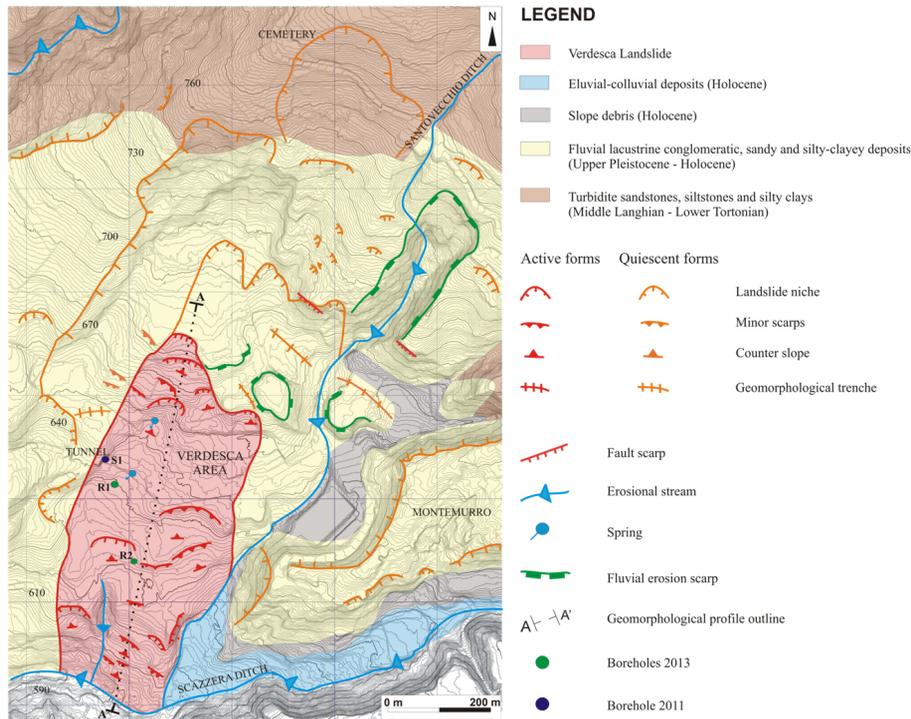
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**Figure 9.** Geomorphological sketch map. The geomorphological profile outline along the A–A’ trace is illustrated in Fig. 13.

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**Figure 10.** Deformation and warping evidences on the road tunnel (a), retaining walls (b), and old building (c and d).

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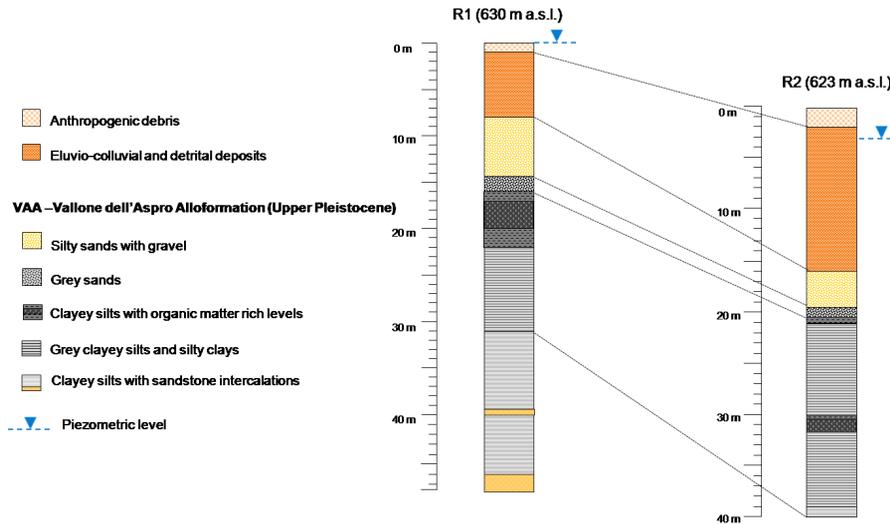
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**Figure 11.** Main stratigraphic features of the logs reconstructed along the R1 and R2 boreholes.

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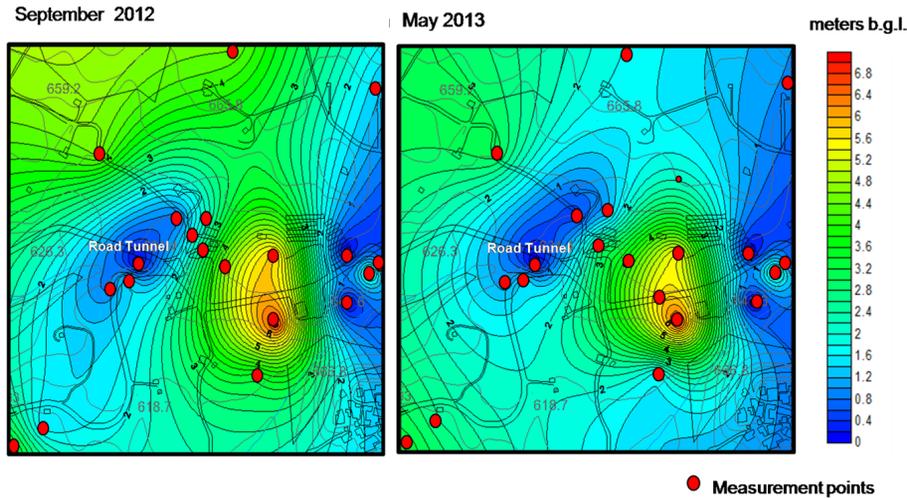
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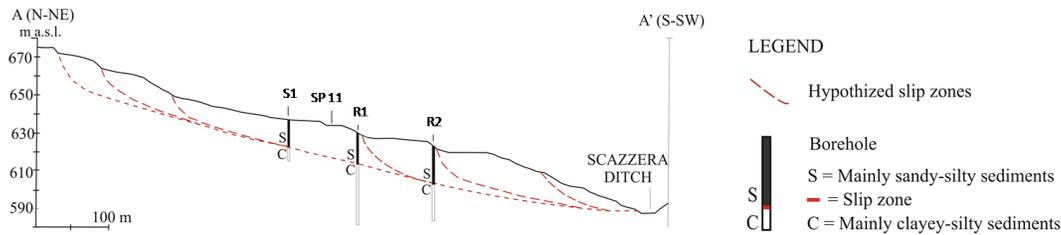
**Figure 12.** Isopiezometric maps.

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**Figure 13.** Geomorphological profile (outline A–A' in Fig. 9).

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