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To cite this article: Luigi Borrelli, Gianfranco Nicodemo, Settimio Ferlisi, Dario Peduto, Silvio Di Nocera & Giovanni Gullà (2018) Geology, slow-moving landslides, and damages to buildings in the Verbicaro area (north-western Calabria region, southern Italy), Journal of Maps, 14:2, 32-44, DOI: [10.1080/17445647.2018.1425164](https://doi.org/10.1080/17445647.2018.1425164)

To link to this article: <https://doi.org/10.1080/17445647.2018.1425164>



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Geology, slow-moving landslides, and damages to buildings in the Verbicaro area (north-western Calabria region, southern Italy)

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ABSTRACT

This paper presents a mass movement inventory map at 1:5000 scale of the Verbicaro area (about 13 km²) located in the Calabria region (southern Italy). The **Main Map** results from the visual interpretation of aerial photographs, multi-temporal geomorphological field surveys, and field investigations of damage suffered by buildings. Some 53% of the study area is affected by a total of 252 landslides, comprising different types, state of activity, and size. The mapped landslides, mainly complex type, involve low-grade metamorphic rocks; among these, 15% are active and slow-move on pre-existing sliding surfaces. Moreover, out of 492 surveyed buildings, 347 are located on landslide-affected areas and experienced damages covering a broad range of severity levels. The **Main Map** can represent a useful tool for authorities in charge of land-use planning and urban management and can be used to pursue landslide risk analyses.

ARTICLE HISTORY

Received 25 July 2017
Revised 22 December 2017
Accepted 4 January 2018

KEYWORDS

Geology; slow-moving landslides; building damage survey; mapping; GIS

1. Introduction

Mass movement inventory maps, produced using conventional methods (Guzzetti *et al.*, 2012), depict the distribution, type, size, state of activity of landsliding in a given area; they represent an essential tool to predict the spatial–temporal evolution of landscapes and, more generally, to properly carry out landslide susceptibility, hazard and risk analyses (Corominas *et al.*, 2014; Fell *et al.*, 2008). Their usefulness is particularly pronounced in very complex geological contexts where urbanized areas are affected by mass movements.

This is the case of the Calabria region (southern Italy, **Figure 1**) where widespread landslides of different type, often spatially interconnected and superimposed, involve low-grade metamorphic rocks (Antronico *et al.*, 2013, 2015; Borrelli & Gullà, 2017; Borrelli & Muto, 2017; Borrelli, Antronico, Gullà, & Sorriso-Valvo, 2014, 2015; Calcaterra & Parise, 2005; Conforti, Muto, Rago, & Critelli, 2014; Dramis & Sorriso-Valvo, 1994; Gullà *et al.*, 2000; Gullà, Ferlisi, Nicodemo, & Peduto, 2017; Gullà, Peduto, Borrelli, Antronico, & Fornaro, 2017; Ietto, Perri, & Cella, 2016; Sorriso-Valvo & Tansi, 1996). These rocks, due to both their intrinsic lithological characteristics and the complex geological processes that took place in Calabria during the Neogene–Quaternary period (Bonardi *et al.*, 1982), are mainly

constituted by a ‘mélange structure’ made up of degraded, broken and fissured phyllites embedding blocks, and fragments of different nature (e.g. slates and metacarbonates). The development of widespread landslides is further promoted and controlled by steep slope angles, rugged topography, tectonics, river deepening, and erosion at the toe of slopes.

Within this peculiar geological context, the Verbicaro study area (13 km²), located in the north-western border of Calabria region (**Figure 1**), is a representative case study. In particular, the urbanized area (including a historic centre – dating back to the second half of the fourteenth-century BC – and newly developed facilities) has been suffering from mass movements for some time. Consequently, the Central Government included the municipality of Verbicaro in the list – never implemented – of the centres that had to be relocated to more stable areas (Italian Law No. 445 dated 9 July 1908). During recent decades, many buildings have been damaged and the municipal council delivered several evacuation/repair/demolition ordinances. However, the seriousness of the problem largely increased since the early 1960s, due to the urban sprawl towards the unstable slopes located in the area north-west of the historic centre (**Figure 1**) where some reinforced concrete buildings experienced

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Supplemental data for this article can be accessed at <http://dx.doi.org/10.1080/17445647.2018.1425164>

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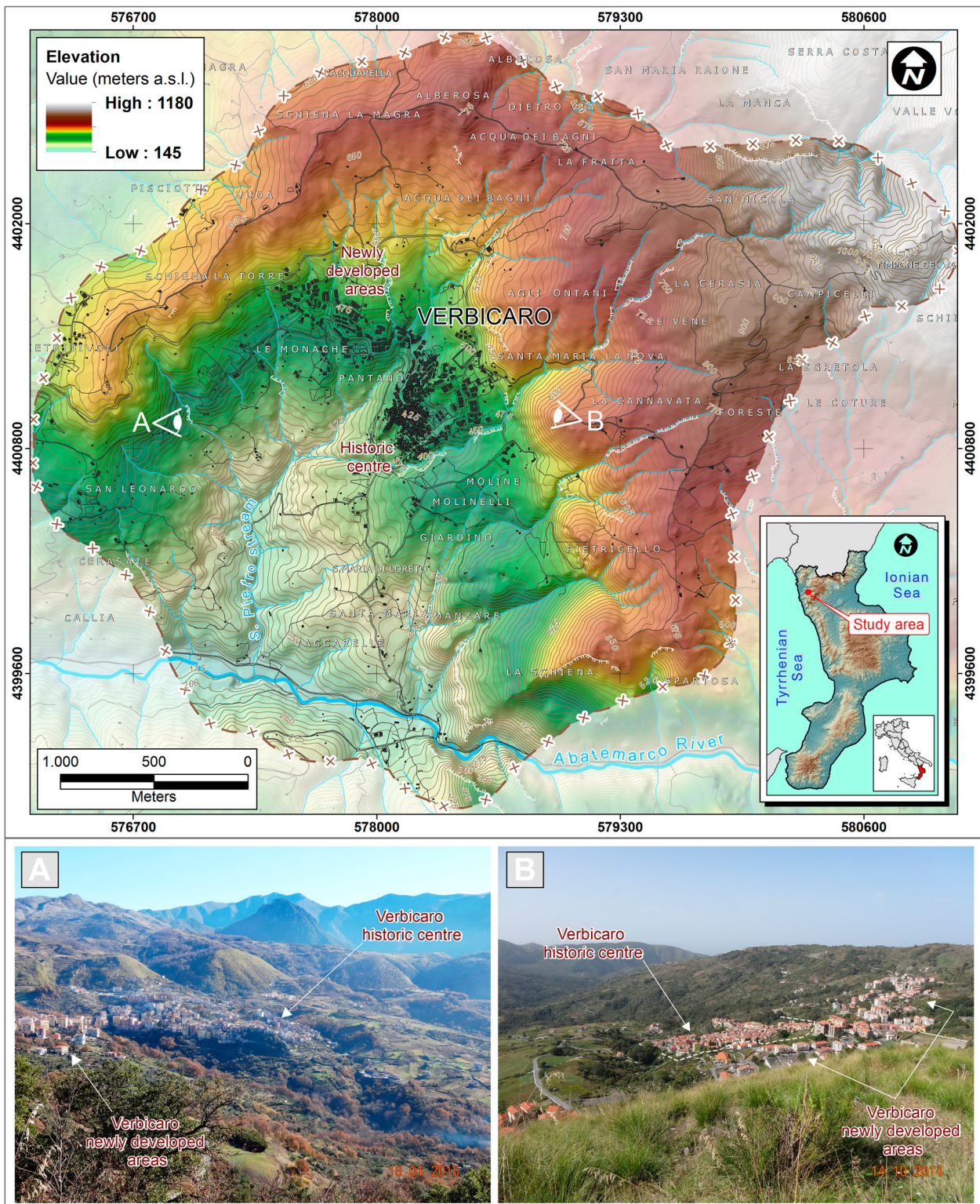


Figure 1. Location of the Verbicaro study area (north-western sector of Calabria region, southern Italy).

damage compromising their stability. The urbanization process stopped about 15 years ago.

This paper is aimed at both reconstructing the geotectonic setting and recognizing/mapping the mass movements that affect the Verbicaro study area, that persistently cause damage to buildings (Ferlisi et al., 2015; Nicodemo, Peduto, Ferlisi, Gullà, et al., 2017). The collected data are stored and managed in a Geographic Information System (GIS) to produce the Main Map.

2. Materials and method

The methodological approach followed to produce the mass movement inventory map of Verbicaro study area includes three sequential steps.

First, geological investigations were carried out using aerial photo interpretation and field surveys, to both investigate and verify the morphological evidence related to tectonics, as well as to identify faults and rock types.

Second, a mass movement inventory map of the study area was generated on the basis of conventional geomorphological criteria that benefited from the use of information gathered from both the interpretation of multi-temporal stereoscopic aerial photographs (1:25,000 and 1:33,000 scale black-and-white and 1:15,000 scale colour aerial photographs, taken from 1955 to 2001) and detailed field surveys carried out from April 2014 to February 2015. Type and state of activity of landslides were established according to the classification proposed by Cruden and Varnes (1996), and adopting geomorphological criteria based on field recognition and freshness of the topographic signatures typical of gravity-related landforms (Brardinoni, Slaymaker, & Hassan, 2003; Brunnsden, 1993; Rib & Liang, 1978). The latter include scarps, conjugate scarps, step terraces, irregular slope profiles (alongside convex or concave forms), ground cracks, slope ruptures, and changes in the drainage network.

Finally, we improved the previously generated mass movement inventory map on the basis of damage (and its severity level) data recorded to exposed buildings of the Verbicaro urbanized area. Note that carrying out this activity generally requires a deep knowledge of relevant factors dealing with both landslides (type, geometrical and kinematical characteristics) and interacting buildings (materials, foundation type, number of floors, state of maintenance) as well as information on their relative location within the landslide-affected area (Fell et al., 2008). Moreover, the damage severity level of a given building may result from several concurrent causes and its estimation may be hampered by maintenance and/or renovation works that might influence the observation of the ‘real’ crack patterns. On the other hand, the approach to be followed for damage recording and the classification system to be adopted for ranking the damage severity level are closely related to the scale of work (and, therefore, to the analysis purposes) as well as to the available amount of time and money. In this regard, the approaches based on the visual inspection of crack patterns exhibited by building façades are particularly useful at large (municipal) scale since they allow a fast and easy way to apply damage recording (Cooper, 2008). Accordingly, ad hoc predisposed fact-sheets (Ferlisi et al., 2015; Nicodemo, Peduto, Ferlisi, Gullà, et al., 2017), filled in during *in situ* surveys (carried out with a multi-temporal surveys from April 2013 to October 2014), were adopted together with a coherent classification system of the recorded damage severity levels. In particular, the latter are distinguished in six classes adapted from those provided by Burland, Broms, and de Mello (1977): D0 = negligible; D1 = very slight; D2 = slight; D3 = moderate; D4 = severe; D5 = very severe. The D0-D1-D2 damage severity levels refer to aesthetic consequences characterized by hairline/fine cracks which can be easily treated during

normal decoration or require easy repair work. Starting from the D3 moderate damage level, when functional consequences are expected, maintenance works are necessary. Once the D4 and D5 severity levels are attained, the damage can compromise the building stability.

The Main Map is finally generated on a topographic base at 1:5000 scale (Technical Regional Map – CTR) and implemented in a Geographic Information System (GIS) using a 5 m resolution digital elevation model (DEM). All the collected data are mapped (as polygon or polyline features) and coded in UTM-WGS84 coordinate system.

3. Geology and tectonics

The geological setting of the study area (Figure 2) is characterized by the presence of Meso-Cenozoic sedimentary–metasedimentary successions related to the uppermost part of the Lungro-Verbicaro Unit (Iannace et al., 2005, 2007).

The sequence starts with a thick dolomite interval, covering the Norian and the Rhaetian, made up of platform, margin and slope to restricted basin facies (Ietto & Ietto, 1998; Ietto, Barillaro, Calligaro, & Mancuso, 1992; Perri, Mastrandrea, Neri, & Russo, 2003) consisting of grey to dark dolomite, well bedded (10–30 cm strata) and graded (Figure 3(A)), or in the form of massive intervals (Figure 3(B)) reaching a total thickness up to 500–600 m (Ietto & Ietto, 2011).

The dolomitic succession passes gradually upward (e.g. *La Cannavata* locality), into the *Grisolia* Formation (upper Norian/Rhaetian–Hettangian, Damiani, 1970) comprising alternating dolomite and limestone (5–40 cm in thickness, Figure 3(C)) with intercalations of reddish and yellowish marl strata (10–15 cm thick) evolving upward to thick bedded dark-grey to black coarsely crystalline limestone (strata of 70–140 cm in thickness), and grey limestone at top of the formation.

The post-Triassic part of the sequence – represented by a cherty limestone succession (*Calcari con Selce* Fm), Jurassic (Lias-Dogger) in age (Compagnoni & Damiani, 1971), reaching a total thickness up to 140–160 m – is in stratigraphic continuity or lies locally above an angular unconformity. The cherty limestone succession consists of well-bedded grey to dark limestone and metalimestone with beds (Figure 3(D)) and chert nodules (Figure 3(E)) predominantly of whitish colour, oolitic limestone and graded calcarenite with cherty fragments.

A disconformity separates these layers from the upper part of the succession, represented by the *Colle Trodo* Formation (Iannace et al., 2007). Its base consists of coarse carbonate conglomerate (the *Brèche à silex* of Grandjacquet & Grandjacquet, 1962 or *Brecce Poligeniche* of Damiani, 1970) of Maastrichtian–Palaeocene age, and thickness between 40–60 m. The

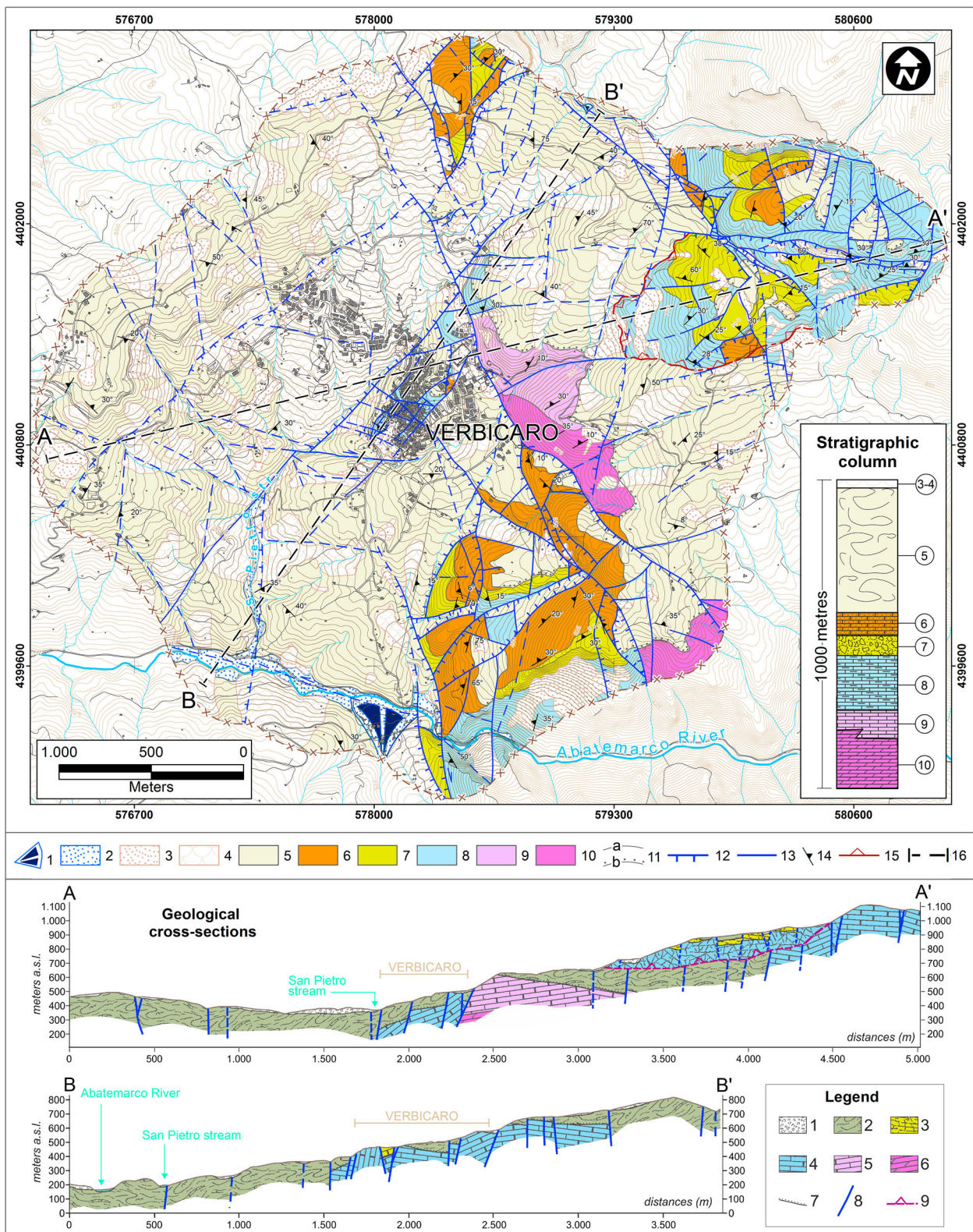


Figure 2. Geo-structural map of the Verbicaro study area. Legend: (1) debris fan (Holocene); (2) alluvial deposits (Holocene); (3) colluvial deposits (Holocene); (4) landslide debris (Holocene); (5) metapelites and metarenites containing calcarenite and calcirudite beds (Scisti del Fiume Lao Fm, early Miocene); (6) red and green metapelites with beds of calcareous turbidites grading upward to yellowish metamarls and grey/dark crystalline limestones (upper part of the Colle Trodo Fm, Middle Eocene–Aquitainian); (7) coarse carbonate conglomerates or Breccie Poligeniche of Damiani (1970) (lower part of the Colle Trodo Fm, Maastrichtian–Palaeocene); (8) grey to dark cherty limestones (Calcarei con Selce Fm, Lias-Dogger); (9) alternating dolomites and limestones with intercalations of reddish and yellowish marls strata (Grisolia Fm, upper Norian/Rhaetian–Hettangian); (10) grey to dark dolomites (Norian); (11) stratigraphic boundary (a) and (b) unconformity; (12) normal fault; (13) fault with undetermined kinematics; (14) attitude of strata or layering; (15) gravity-driven contact; and (16) cross-section. Geological cross-sections. Legend: (1) landslide debris; (2) Scisti del Fiume Lao Fm; (3) Breccie Poligeniche; (4) Calcarei con Selce Fm; (5) Grisolia Fm; (6) Norian dolomite; (8) fault; and (9) gravitational slope failure.



Figure 3. Lithology outcropping in the Verbicaro study area: (A) well-bedded grey to dark dolomites (Norian); (B) massive dolomites (Norian); (C) alternating dolomites and limestones with intercalations of reddish and yellowish marls strata (Grisolia Fm, upper Norian/Rhaetian–Hettangian); (D) grey to dark limestones with cherty beds and nodules (E) (Lias-Dogger); (F) coarse breccia with calcareous and dolomitic clasts (Maastrichtian–Palaeocene); (G) yellowish metamarls and grey/dark crystalline limestones (upper part of the Colle Trodo Fm, Middle Eocene–Aquitainian); (H) Stratigraphic contact between Colle Trodo and Scisti del Fiume Lao Fms (Alberosa locality); (I) metapelites and metarenites (Scisti del Fiume Lao Fm, early Miocene); (J) colluvial deposits (Holocene); (K) landslide debris (Holocene); (L) NW–SE trending normal fault; (M) particular of the fault plane of photo (L); (N) NW–SE trending fault zone; (O) NE–SW fault plane overprinted by dip-slip slickenlines; (P) right-lateral transcurrent indicators overprinted by dip-slip striae; and (Q) high-angle reverse fault cut and offset by NW–SE trending shear zones.

breccia clasts (diameters of 2–30 cm) consist mainly of platform limestone but locally fragments of chert are also present (Figure 3(F)). These rudites are followed abruptly by a sequence (which reaches a total thickness of about 60–80 m) comprising red and green metapelite with frequent beds of calcareous turbidites grading upward to yellowish metamarl and grey/dark crystalline limestone (Figure 3(G)). The abundant macro foraminifera, characterizing the latter interval, indicate an Eocene to early Miocene age (Grandjacquet & Grandjacquet, 1962). A refined Middle Eocene to Aquitanian age was obtained by nannoplankton biostratigraphy (D’Errico, 2004).

The *Colle Trodo* Fm grades upward to metapelite and metarenite containing some calcarenite and calcirudite beds with micro foraminifera of early Miocene age (the *Flysch del Lao* of Damiani, 1970 or *Scisti del Fiume Lao* Formation of Burton, 1971). Even though the basal contact of the *Scisti del Fiume Lao* is often sheared, the stratigraphic relationship with the underlying formation can be observed at *Contrada Alberosa*, north of Verbicaro village (Figure 3(H)). In particular, above a few metres of turbiditic calcarenite that mark the beginning of the *Scisti del Fiume Lao* Formation, green and grey metapelite (often completely degraded and argillified) and marl are found with thin intercalations of brown metarenite with parallel and cross laminations (Figure 3(I)). Calcarenite and calcirudite beds often occur throughout the Miocene succession. Biostratigraphic analysis of the nannoplankton allowed us to date this interval as not older than Aquitanian–Lower Burdigalian, based on the presence of the index species marker *Discoasterdruggii* and *Helicosphaeracarteri* (Iannace et al., 2007).

Finally, widespread Holocene colluvial soils (Figure 3(J)), slope and landslide debris (Figure 3(K)) predominantly mantle the *Scisti del Fiume Lao* Formation; these remoulded lithotypes form a ‘mélange structure’ made up of blocks and fragments of different nature (e.g. phyllite, slate, and metacarbonate) in a primarily clayey matrix, mainly resulting from the degradation of phyllite.

From a tectonic point of view, the study area is cross-cut by two main fault systems mainly striking NW–SE and NE–SW (Figure 2). The NW–SE fault system, clearly recognizable on a morphological basis, strongly influences the morphology and the drainage network of the study area juxtaposing the *Scisti del Fiume Lao* Formation against the underlying Mesozoic successions (Figure 2). The NW–SE fault system is arranged into a south-westward stepwise fault segment, whose master fault is represented by 3-km-long, SW-dipping normal fault which crosses the central portion of the study area (directly upstream of the Verbicaro town, Figure 3(L)). This first-order fault is characterized by a well-developed escarpment, with triangular and/or trapezoidal facets. At the mesoscale, fault planes

strike from N110E to N160E and dip 50°–80° mostly toward the SW; the same ones are characterized by sub-horizontal grooves and striae documenting left lateral strike-slip motions, often superimposed by normal sub-vertical slickenlines (Figure 3(M)) that testify mainly normal kinematics induced by the last Quaternary deformational events (Ietto & Ietto, 2011).

Fault zones linked to the NW–SE fault system are commonly characterized by brittle deformation (Figure 3(N)), including mesoscopic and microscopic pervasive fractures, slickensides and fault rocks (e.g. breccia and cataclastite).

The second fault system, morphologically less evident and more ancient than the previous one, shows a NE–SW trend and dip toward NW and SE, respectively; it can be identified by the pattern of second order streams flowing toward the Abatemarco River (Figure 2). The main fault segment belonging to this system may be morphologically identified with the San Pietro channel which essentially splits the new and old part of Verbicaro, and juxtaposes the *Scisti del Fiume Lao* Formation with the underlying Mesozoic and Palaeogene carbonate sequences (Figure 2). At the mesoscale, the fault planes in some cases show diversified and overlapping kinematics. The chronological analysis of such elements indicates that this system presents right-lateral motion, followed by dip-slip displacements, caused by passive reactivation of the still ongoing tectonics (Figure 3(O,P)).

In addition, transpressional phases along the NE–SW fault system have most likely induced the extrusion of the Mesozoic Carbonate rocks over the *Scisti del Fiume Lao* Formation in some sectors of the study area, as well as observed in the old historic centre of Verbicaro, where a spectacular reverse fault plane is recognizable in outcrop (Figure 3(Q)).

4. Geomorphological features and mass movement inventory map

The topographic relief of the Verbicaro study area ranges from 145 to 1180 m of elevation above sea level (Figure 1).

The morphology (Figure 1) is very complex and strongly controlled by geology and tectonics (Ietto & Ietto, 2011). Particularly, the Quaternary tectonic uplift (Robustelli, Muto, Scarciglia, Spina, & Critelli, 2005; Scarciglia et al., 2016; Tortorici, Monaco, Tansi, & Cocina, 1995; Westaway, 1993) and the related deepening of the hydrographic network increased the relief energy – giving rise to steep slopes and deeply cut valleys (e.g. Abatemarco River and San Pietro stream) – and made the slopes prone to failure (Cigna, Bianchini, & Casagli, 2013; Conte, Dente, & Guerricchio, 1991; Ferlisi et al., 2015; Guerricchio, Mastromattei, Ronconi, & Tucci, 1996; Gullà et al., 2000; Nicodemo, Peduto, Ferlisi,

Gullà, et al., 2017). Slope gradient depends on the hardness of the different lithological units. Low-relief landscapes characterized by a milder morphology with gentle slopes are found where extremely deformed and chaotic phyllite, marly–clayey and shale, belonging to the *Scisti del Fiume Lao* Formation, diffusely crop out (for about 70% of the study area). High-declivity slopes consistently correspond to outcrops of harder rocks (i.e. Mesozoic–Palaeogene successions, this latter outcropping for the remaining 30% of the study area), generally forming steep slopes, scarps, and cliffs.

The mass movement inventory map (Figure 4 and Main Map) shows 252 landslides (of different type, size, age, and state of activity), with an average density of about 21 landslides/km². In particular, the inventory shows 167 slides, 76 complex/compound phenomena, 5 shallow landslide zones, and 3 wide medium-deep landslide zones both affected by creep processes, and a large compound translational block slide (Figure 4). The mapped landslides range in size from 5 × 10² m² to 4 × 10⁵ m², totally affecting an area of 6.76 km², namely the 53% of the whole study area. The analysis of the inventory map revealed that 15% of the mapped landslides can be considered as active and slow-moving on pre-existing sliding surfaces (Cigna et al., 2013; Ferlisi et al., 2015; Nicodemo, Peduto, Ferlisi, Gullà, et al., 2017). The landslide activity effects are well recognizable in the whole study area and mainly consist of deformation and cracking of buildings and roads, and bending of trees.

The *Scisti del Fiume Lao* Formation, consisting of degraded phyllite, slate, and metacarbonate, is extensively affected by several mass movements classified as complex (slide/flows), slides, and landslide zones affected by creep processes; moreover, a high spatial persistence of medium-deep slope failures of different generations inside pre-existing older and deep landslides can be observed (Figure 4).

An extensive landslide area affected by deep creep movements, and partially masked by the superimposition of several landslides, affects the slope on the hydrographic right of the S. Pietro stream (Figures 4 and 5(A)). This landslide area may be easily identified by aerial photographs through their effects on the slope morphology, such as irregular slope profiles (undulation and swells of the topographic surface), counter slopes, changes in the drainage network, and toe bulging.

Complex landslides (largely classifiable as roto-translational slides evolving into earth/debris flows) are randomly widespread in the whole study area (Figure 4), and mainly located within the morphological hollows. Characteristic features of these mass movements consist of gently hummocky topography and ridges of accumulated material in the toe area, often causing the deviance of river channels. Many

complex-type landslides show amphitheatre-shaped upper scarps and elongated bodies (having lengths ranging from 100 to 1500 m) and accumulation zones, ending with U-shaped toes (Figures 4 and 5(B,C)). Two wide, old and dormant juxtaposed complex phenomena, detected by means of aerial photo interpretation and field controls, are located within the landslide zone previously described (Figure 5(A)), and affect all the new developed area of Verbicaro, where detrital covers outcrop.

Deep and medium-deep roto-translational slides (the most common type of landslide in the study area) are widespread along slopes of the San Pietro stream (Figure 4). Characteristic features of this type of mass movements can be easily identified by aerial photographs showing their effects on the slope morphology (Figure 5(D,E)), such as semicircular main scarps, secondary downhill and uphill-facing scarps, counter slopes, landslide terraces, irregular slope profiles, changes in the drainage network, and toe bulging (Cruden & Varnes, 1996; Hungr, Leroueil, & Picarelli, 2014; Hutchinson, 1968, 1988; Varnes, 1978). Many active slides involve and cause damage to buildings (Figure 5(F,G)) and infrastructure (Figure 5(H,I)).

The Mesozoic–Palaeogene carbonate hillslopes are usually affected by limited landslide phenomena (of slide and complex type) that mainly involve the detrital covers (Figures 2 and 4). Nevertheless, combining photo interpretative analyses and field checks it was possible to detect and map – in the eastern portion of the study area, about one kilometre upstream of Verbicaro historic centre – a spectacular example of large and dormant compound rock-block slide phenomenon (maximum length and width, respectively, of 1.5 km and 700 m), characterized by topographic signatures typical of gravity-related landforms including scarps, conjugate scarps, trenches (partially covered by colluvial deposits), and irregular topography where several blocks of carbonate rocks, of sizes variable between few cubic centimetres and decimetres, were observed in outcrop (Figure 5(J,K)). In addition, the geological survey allowed identifying the inverted overlapping relationship, due to gravity-driven processes, between the Mesozoic carbonate units and the *Scisti del Fiume Lao* Formation (Figure 5(L)). This assumption was validated by the Persistent Scatterer Interferometry (PSI) performed by Cigna et al. (2013).

Finally, in the same context of Meso-Cenozoic carbonate rocks, small and localized toppling and rock falls, whose extension is not easy to map, were observed. Particularly, these types of phenomena were found along the crest of a high and narrow ridge (made by sub-vertical strata of limestone), that is bordered by steep cliffs, on which the historic centre of Verbicaro rises (Figure 5(M)). On its top, the narrow

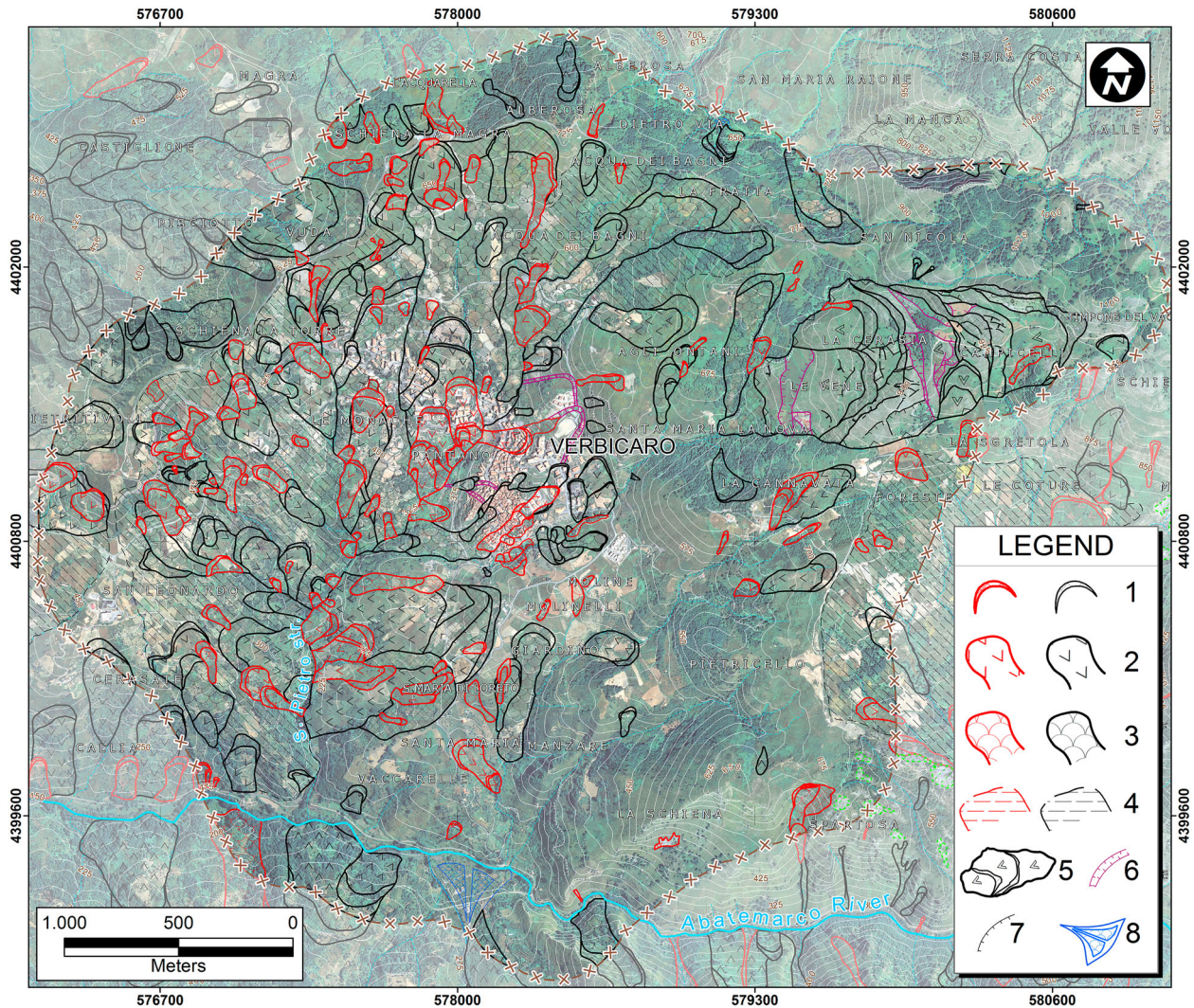


Figure 4. Mass movement inventory map of the Verbicaro study area: (1) active (red) and dormant (black) landslide scarp; (2) active (red) and dormant (black) slide; (3) active (red) and dormant (black) complex landslide; (4) active (red) and dormant (black) landslide zone affected by creep processes; (5) dormant block slide; (6) trenches; (7) secondary scarps; and (8) dormant debris fan.

ridge is characterized by joints opening phenomena (Figure 5(M)) that along their edges give rise to disarticulated blocks and wedges (often separated by steeply dipping planes) in an unstable state of equilibrium, that are very prone to generate planar failures, wedge slides, falls, and topples (Figure 5(N,O)). The fractures opening phenomena tend to close toward lower parts of the rocky crest.

5. Field investigations of damage to buildings

Many structures, especially old buildings resting on inadequate foundations but also modern buildings not appropriately designed to bear displacements induced by landslides, are prone to damage (Nicodemo, Peduto, Ferlisi, & Maccabiani, 2017; Peduto, Nicodemo, et al., 2016; Peduto, Nicodemo, et al., 2017). Therefore, their study can provide useful information for retrieving cause–effect relationships (Nicodemo, Peduto, Ferlisi, & Maccabiani, 2017; Nicodemo, Peduto, Ferlisi, Gullà, et al., 2017; Peduto, Ferlisi, et al.,

2017; Peduto, Nicodemo, et al., 2017; Peduto, Pisciotta, et al., 2016) as well as detecting/mapping the landslide boundaries (Antronico, Borrelli, Coscarelli, & Gullà, 2015) – not easily recognizable in urban environments – and the definition of their state of activity (Cascini et al., 2013; Peduto, Borrelli, Antronico, Gullà, & Fornaro, 2016). Moreover, the knowledge of both spatial distribution and severity levels associated to damage suffered by affected building allows a better understanding of the landslide mechanisms.

Accordingly, in order to improve the mass movement inventory map generated on the basis of geomorphological criteria, an extensive campaign of surveys aimed at recording and classifying the damage to buildings of the Verbicaro urbanized area was carried out. The campaign, consisting of multi-temporal surveys lasting from April 2013 to October 2014, first focused on buildings included in evacuation/repair ordinances delivered by the municipal council and later extended to the remaining buildings composing the Verbicaro urbanized area. To this aim, ad hoc predisposed fact-sheets (Ferlisi et al., 2015; Nicodemo, Peduto, Ferlisi,

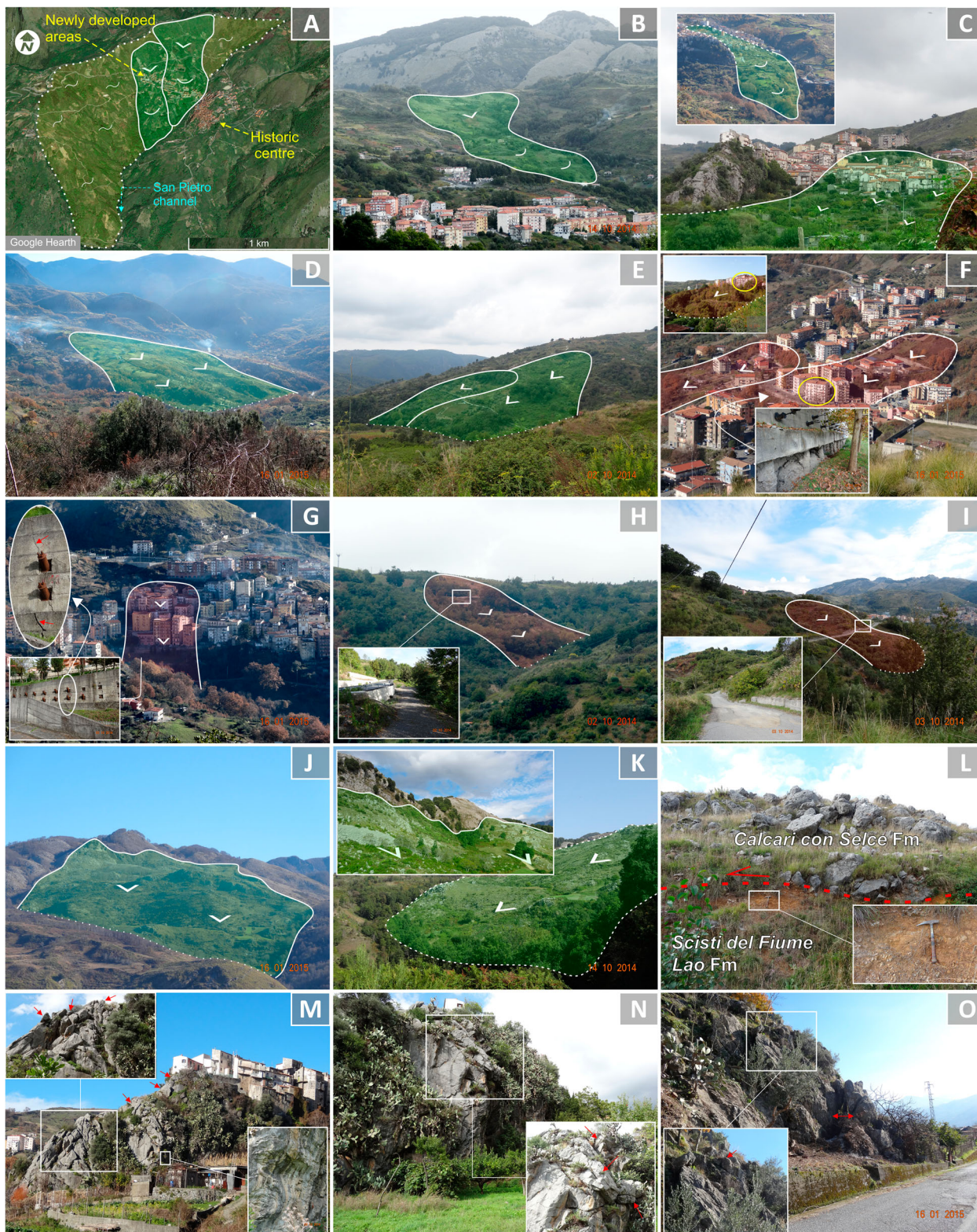


Figure 5. Slope instability phenomena widespread in the study area. (A–I) examples of landslides involving the Scisti del Fiume Lao Fm: (A) Google Earth image of the extensive landslide zone (on which two large, complex and dormant landslides are superimposed) that affected the entire right slope of the S. Pietro stream; (B–C) typical features of two complex and dormant landslide phenomena showing amphitheatre-shaped upper scarps and elongated bodies; (D–E) examples of large and dormant slides and their effects on the slope morphology; (F–G) active slides involving respectively the newly urbanized area and the historic centre; (H–I) active slides involving respectively provincial and municipal roads. (J–O) landslide phenomena involving the Mesozoic carbonate rocks: (J–K) panoramic views of a spectacular example of large and dormant compound rock-block slide phenomenon; (L) gravity-driven superimposition between the Mesozoic carbonate units and the Scisti del Fiume Lao Fm; (M) open fractures and disarticulated blocks on the top of the narrow ridge (made by subvertical dipping limestones strata) on which the historic centre of Verbicaro rises; and (N–O) blocks and wedges prone to generate planar failures, wedge slides, falls and/or toppling along the borders of the narrow ridge.

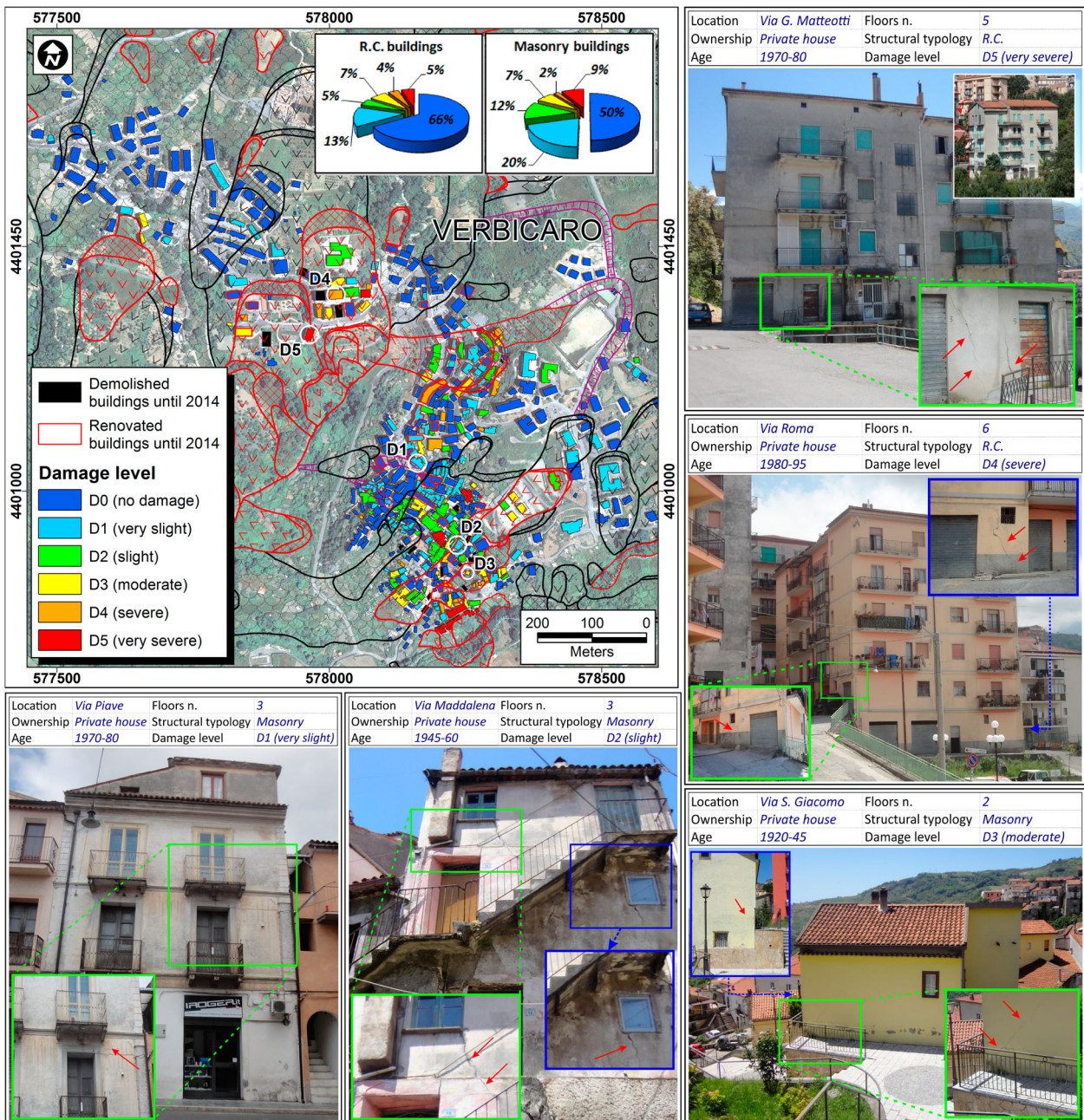


Figure 6. Map of surveyed buildings distinguished according to the recorded damage severity (D0–D5) based on data collected during *in situ* damage survey via ad hoc predisposed fact-sheets for both reinforced concrete and masonry buildings.

Gullà, et al., 2017) were completed for a total of 253 reinforced concrete and 239 masonry buildings (Figure 6). These fact-sheets consist of different sections that allow gathering information on: location of the building and its description in terms of structural type and geometrical characteristics; age of construction and occupancy type; damage (in terms of cracks and/or disjunction in the outer walls, distortions and/or tilt, partial collapse) recorded by a visual inspection of the façades and later ranked according to the adopted classification system.

Data collected during the damage survey highlight that 34% (Figure 6) out of the total surveyed reinforced concrete buildings – mainly built in the early 1960s (up to 7–8 floors) in the newly developed areas

(Figure 1) – and 50% (Figure 6) of the masonry buildings (up to 3 floors) mainly located in the historic centre (Figure 1) exhibit damage whose severity level is higher than D0. In particular, 197 out of 253 reinforced concrete and 150 out of 239 masonry surveyed buildings, are within slow-moving landslide-affected areas and experienced the higher severity levels (up to D5) when they are located near the scarps or along landslide boundaries. Furthermore, the collection and analysis of the information on evacuation/repair/demolition ordinances delivered by the municipal council in the period 1989–2009 on many masonry buildings of the historic centre as well as on new reinforced concrete buildings built in the north-western urban area, corroborated by the results of *in*

situ surveys, allowed identifying the buildings that were demolished or subjected to renovation works (Figure 6).

The collected data proved helpful for landslide inventory mapping activities especially in the historic centre (Figure 1) where the urban fabric is characterized by contiguous masonry buildings that make difficult – on the basis of geomorphological criteria only – the recognition of the landslide boundaries and, more in general, the distinction of different landslide bodies. On the other hand, in the newly developed area (Figure 1) where a given building can be considered as isolated (i.e. its behaviour is independent from adjacent buildings), the multi-temporal damage surveys led to a reliable identification of the different features pertaining to a given landslide (Cruden & Varnes, 1996) along with the definition of its state of activity.

6. Conclusions

This paper focused on the generation of a mass movement inventory map concerning the Verbicaro study area that extends for about 13 km² in the northern Calabrian Coastal Range (southern Italy).

This area is a representative case study where lithology (i.e. degraded, broken, and fissured phyllites belonging to the *Scisti del Fiume Lao* Formation), tectonic setting, high relief and steep slopes predispose and control the development of widespread landslides.

The **Main Map** was obtained by combining the information gathered from multi-temporal aerial photo interpretation and field surveys with data on the damage severity levels suffered by landslide-exposed buildings. A total of 252 landslides (covering about 53% of the whole study area) of different types, states of activity, and sizes were mapped. They commonly consist of multiple and superimposed bodies, thus confirming that the spatial distribution of recent landslides is influenced by one of the pre-existing phenomena; moreover, 15% out of mapped landslides were recognized as active and very slow-moving on the buried sliding surfaces. On the other hand, 347 buildings (197 reinforced concrete and 150 masonry), located within slow-moving landslide-affected areas, were damaged; among these, 34% of reinforced concrete buildings and 50% of masonry ones exhibited damage levels spanning from very slight to very severe. The collected data allowed us to improve the mapping of landslide boundaries – not easily recognizable in urban environments only using geomorphological criteria – and defining, in many cases, their state of activity.

The produced **Main Map** can represent a useful tool to carry out consequence analyses aimed at identifying and selecting the most appropriate strategies for landslide risk mitigation and properly addressing restoration and adaptation policies.

Software

The mass movement map and related layout (Figures 1, 2, 4, and **Main Map**) were generated via ESRI ArcGIS 10.0. Corel Draw X6 was used for compiling Figures 3, 5, and 6.

Acknowledgements

This work was partially carried out under the Project DTA.AD003.077.001 ‘Tipizzazione di eventi di dissesto idrogeologico’ of the CNR Department of ‘Scienze del Sistema Terra e Tecnologie per l’Ambiente’. The work is also framed within the research agreement between the Research Institute for Geo-Hydrological Protection, National Research Council of Italy and the Department of Civil Engineering of the University of Salerno on ‘Attività di ricerca mirate ad approfondire le conoscenze sulla tipizzazione di movimenti franosi a cinematica lenta e sulla vulnerabilità di strutture e infrastrutture che con essi interagiscono anche mediante l’impiego di tecniche innovative di monitoraggio satellitare e da terra’. The authors wish to thank the Municipality of Verbicaro that has kindly provided the orthophoto (year 2012) used as background of Figures 4 and 6.

Disclosure statement

No potential conflict of interest was reported by the authors.

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