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Mapping landscape evolution in 3D: Climate change, natural hazard and human settlements across the 1618 Piuro landslide in the Italian Central Alps

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Abstract

Natural and anthropogenic mountain landscapes coevolve responding on different temporal scales to climate changes and geodynamics by a series of increments that cause the dynamic association of morphological stabilization surfaces, stratigraphic units and landforms. Understanding the incremental history of palimpsest landscapes helps to recognize and forecast the effects of climate change on the sensitive mountain environments, contributes to archaeological and historical reconstruction and supports management strategies for natural risks prevention and mitigation. The Italian Bregaglia Valley provides an excellent site to unravel the recent/historical increments of evolution of landforms and human settlement, permitting to map the paleo-digital terrain models (DTMs) corresponding to the relevant landscape turning points. After the last de-glaciation, two large-scale landslides reshaped the valley floor, both predisposed by deep-seated gravitational slope deformations and one surely triggered by intense rainfalls. The most recent and impacting event buried in 1618 the rich border town of Piuro, the ancient one occurred in the same area at least 1.5 ka before. Combining stratigraphic, geomorphological, topographic, archaeological and historical data, we drew the paleo-DTMs of the pre- and post-1618 settings of Piuro, sketching the landscape evolution. Since two millennia, human settlements took advantage of the decadal to secular most stable surfaces, represented by the inactive lobes of debris-flow fans, the highest trunk river terraces and the top of humps formed by the ancient landslide body in the valley centre. Stratigraphic relationships, archaeological findings and age determinations show that both landslides diverted the trunk river and covered the existing fan lobes. On a secular timescale, fan progradation and trunk river terracing buried and reworked both the landslide bodies. The paleo-DTMs show their original areal extent and permit to compute their volume and to sketch the setting of the buried Piuro settlements, drawing the changes of the Mera trunk river course and the chronology of activity of the lateral debris-flow fan lobes.

KEYWORDS
Central Alps, human and landscape, landslides, natural hazards, paleo-DTM, palimpsest landscape, Piuro 1618

1 | INTRODUCTION

Landscape of mountain settings is strongly sensitive to climate changes at different temporal scales. Specific landforms develop in chronological sequence, superimposing, erasing or preserving the former ones (Bailey, 2007; Bloom, 2002) giving origin to palimpsest landscapes (Goodfellow et al., 2008; Knight, 2012). The post-glacial landscape of Alpine valleys evolved in a setting of relic Pleistocene glacial features that underwent progressive displacement, erosion and burial by slope instability and alluvial dynamics (e.g., McColl, 2012). Knowing the recent, short-term incremental history of landscape evolution is relevant to understand the response of these environments to climate change, and to forecast type, intensity and rate of dangerous processes and the inherent risks, in order to steer actions for land protection and management.

Mapping landscape modifications contributes also to reconstruct the palimpsest archaeological landscape and the interplay between the geological–geomorphological evolution and the history of human settlement in mountain habitats (e.g., Biagi et al., 2022).

Alpine valleys have always had a central role in the history of populations, as they connect Southern and Central Europe (Freshfield, 1917). Human activities and geological evolution have always been tied in these territories, often not peacefully, as witnessed by the catastrophic events that involved settlements throughout the Alps (Guzzetti, 2000; Luino, 2005). A correlation between ongoing climatic variations and the rising of landslide events has been suggested in several studies in Alpine context (e.g., Crozier, 2010; Evans & Clague, 1994; Soldati et al., 2004; Stoffel & Huggel, 2012). The same correlation could be also true for past events, in turn occurred in variable climatic contexts. Studying these events and the subsequent landscape evolution could hence prove useful to understand the response of Alpine environments, also in a key of future risk reduction.

One renowned case is found in the Italian Bregaglia Valley (Central Alps) whose geomorphological evolution and human presence were controlled by repeated landslide and mass failure events since post-glacial times. The 1618 AD landslide that completely reshaped the valley floor is well documented because it wiped out the famous town of Piuro, remaining impressed into narration and artistic representations. This event represents a geomorphological turning point that provides the physical and chronological key to map the increments of landscape changes predating and postdating the catastrophe.

This work presents an attempt to reconstruct and map the following: (i) the landscape of the area that hosted the village of Piuro; (ii) the topography of the same area immediately after the landslide; and (iii) the geological, geomorphological and anthropogenic modifications that led to the present-day landscape configuration, to sketch the evolution of this territory at the secular scale. Based on a geological and geomorphological approach integrated by archaeological and historical evidence and constraints, this method permits to step back from the present-day setting to the buried and/or eroded topographic surfaces corresponding to significant instants of landscape history. Some remarks were made on the effects of climate fluctuations from the Last Glacial Maximum to the present day, showing an expected correlation between glacial dynamics, intense precipitation and slope instability in the area.

2 | GEOLOGICAL AND GEOMORPHOLOGICAL SETTING OF THE PIURO SITE

Piuro is located in the middle of the E–W-trending Bregaglia Valley near the Italy–Switzerland border. The valley intersects the pile of the Penninic nappes (Figure 1) in correspondence of regional tectonic lineaments. Among them, two played a significant morphogenetic role (Figure 1a), the Forcola Line (Ciancaleoni & Marquer, 2006, 2008; Marquer, 1991; Meyre et al., 1998) and the sinistral strike-slip Engadine Line prolonging westwards into the Gruf Line (GL) (Galli et al., 2013; Schmid et al., 1996; Schmid & Froitzheim, 1993; Schmutz, 1976; Tibaldi & Pasquarè, 2008; Trümpy, 1977; Wenk, 1984).

Evidence for transpressive kinematics has been suggested at least up to the Pleistocene for the GL (Tibaldi & Pasquarè, 2008) that runs parallel to the southern slope of the Bregaglia Valley. The valley flanks show different geology (Figure 1b): gneissic rocks of the Pennine Tambò and Suretta nappes mainly compose the northern one with a main anti-dip-slope foliation. Fracture networks drive the diffuse slope instability, setting landslide scars, scarps and trenches (Pigazzi et al., 2022; Tantardini, 2016). The lower slopes of the southern valley flank are formed by mafic and ultramafic slabs of the Chiavenna Unit, pinched within the gneiss of the Tambò Nappe. The GL puts this complex in contact with the migmatites of the Gruf Complex. Here, the main foliation becomes steeper and steeper and deep-seated gravitational slope deformations (DGSDs) occur (Figure 1c; Pigazzi et al., 2022; Tantardini, 2016; Tibaldi & Pasquarè, 2008). As a consequence, the Bregaglia Valley flanks are asymmetrical, the northern one being steeper and deeply incised and the southern one being gentler and characterized by convex-up landforms in its lower portion (Figure 1c).

The outcropping glacial deposits and the corresponding landforms are attributed to the Last Glacial Maximum (LGM) (Boriani et al., 2012; Gaetani et al., 2012; Michetti et al., 2013), related to a western expansion of the Swiss Engadine Glacier (Bini et al., 2009; Florineth & Schlüchter, 1998, 2000; Tantardini et al., 2022) (Figure 1d). These include ablation tills, lateral moraines, alignments of erratic boulders, sheepback and striated rocks that span from the base of the slopes to elevations above 2000 m a.s.l. (Pigazzi et al., 2022; Tantardini, 2016; Tantardini et al., 2022). Reworked faceted and striated exotic clasts commonly occur within the post-glacial to recent deposits of the valley floor. Large slabs of ablation and sub-glacial till are found within the 1618 Piuro landslide (PL) deposits and traced to the remnants of a glacial terrace underneath the landslide scar on the southern valley slope (Pigazzi et al., 2022). The post-glacial sediments relate to slope instability and alluvial activity of the trunk river (Mera River) and of the debris-flow fans of its steep tributary basins.

Structural, morphological and glacial-related predisposing factors make this territory particularly susceptible to slope instability processes. Indeed, several massive landslides are reported around this area by the Inventario dei Fenomeni Franosi in Italia (IFFI—Italian landslide inventory) (Figure 1c), including the landslide that buried the ancient village of Piuro in 1618. This reflects the intense slope activity that followed the LGM de-glaciation.

3 | METHODS

In order to reconstruct the pre- and post-1618 landscape of the Piuro valley floor, an integrated approach combining stratigraphic, geomorphological, topographic and archaeological data with historical maps

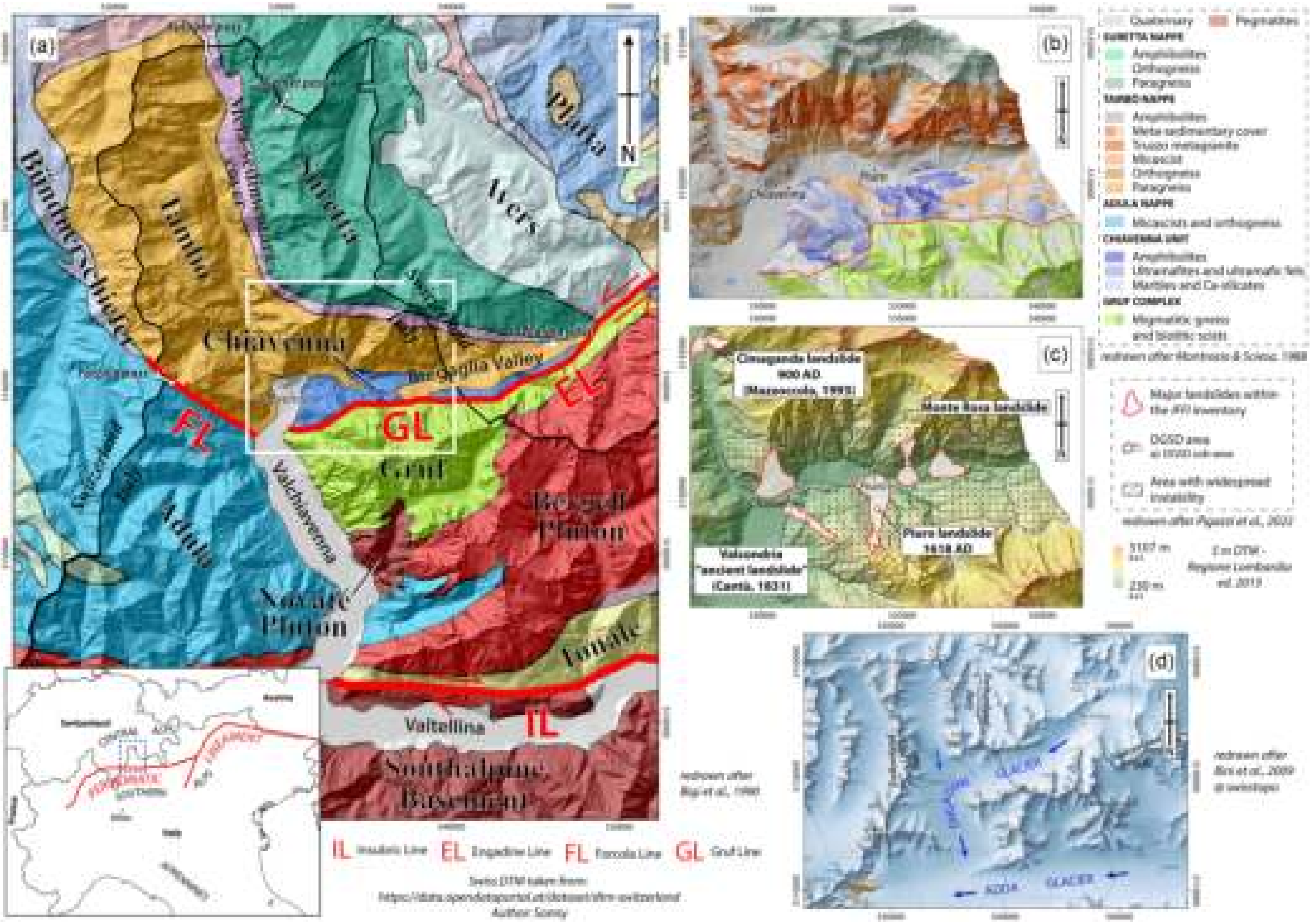

FIGURE 1 (a) Tectonic scheme of the Lepontine–Rhaetian Central Alps across the Swiss–Italian border. Bregaglia Valley runs parallel to the Engadine Line (EL) and its westernmost termination, the Gruf Line (GL). (b) Geological map of the Italian Bregaglia Valley (white frame in [a]). The northern valley slope cuts the Tambò and Suretta nappes; in the southern one, the GL puts in contact the Chiavenna Unit ultramafites and the Tambò Nappe with the gneisses of the Gruf Complex. (c) Deep-seated gravitational slope deformations (DGSDs) affecting the flanks of the valley. Massive landslides reported in the Inventario dei Fenomeni Franosi in Italia (IFFI—Italian landslide inventory) (ISPRA—Regione Lombardia, n.d.) around Piuro are shown. (d) The Engadine–Bregaglia glacier during the Last Glacial Maximum (after Bini et al., 2009).

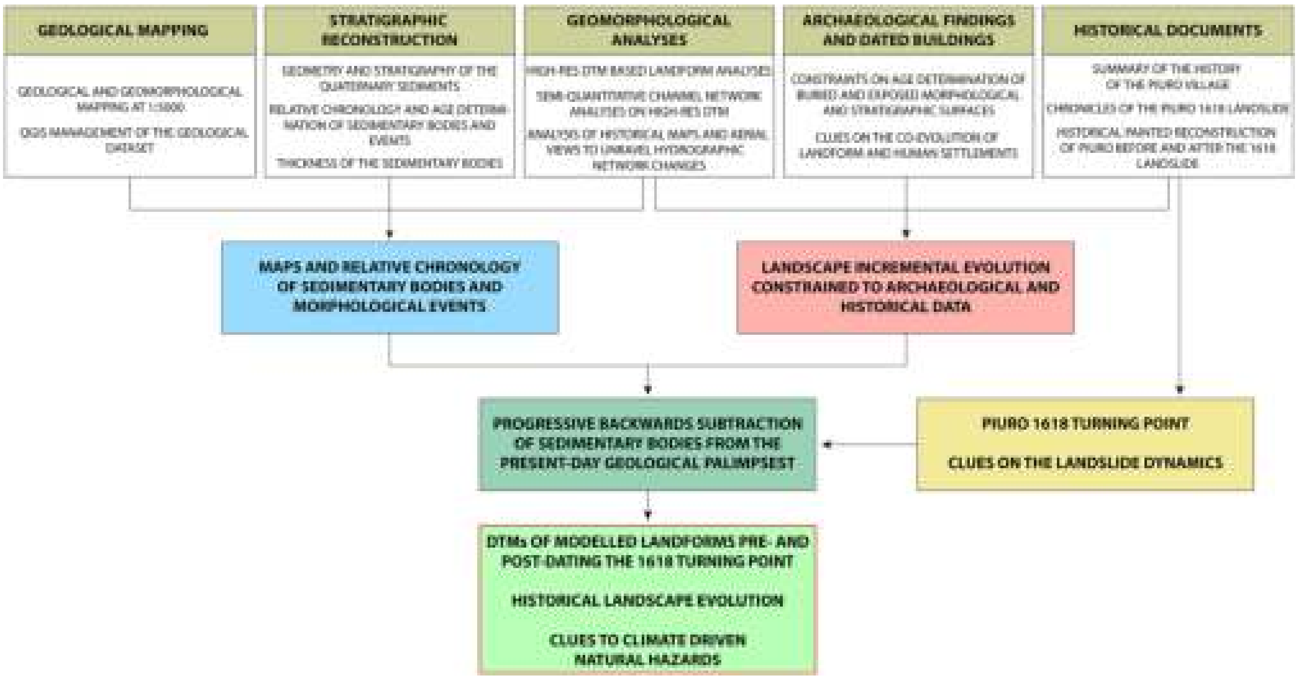

FIGURE 2 Workflow for defining the landscape of Piuro before and after the 1618 landslide.

and iconography has been applied (Figure 2). By progressively subtracting the deposition/erosion landforms and sedimentary bodies, we were able to step back from the present-day setting and gain a better understanding of the landscape before and after the landslide. The dataset and computations were managed in open-source QGIS environment.

The boundaries of all the stratigraphic entities were mapped at 1:5000, to recognize their physical relationships and the sequence of depositional/erosional events. The lithosomes composing the post-glacial unit formerly mapped by Pigazzi et al. (2022) have been separated (debris-flow fan lobes, individual slope and landslide bodies, alluvial terraces and torrential deposits). Stratigraphic logs from two boreholes add sub-surface constraints to the 3D reconstruction of the buried stratigraphic boundaries. This part of the workflow yielded the following: (i) the sequence and relative chronology of activation/deactivation of the individual lobes of the post-glacial debris-flow fans that occupy most of the base of slopes and valley floor, and the related stream avulsions; (ii) the diversions and terracing of the Mera trunk river; (iii) the physical and chronological sequence of landslide events; and (iv) the general relative chronology of superposed landforms.

The field geomorphological analyses were integrated by the study of aerial photographs from 1950s to today and topographic maps available since 1811, to detect the recent variations of the hydrographic network unravelling the recent anthropogenic changes of the landscape.

Field morphological analyses were integrated with topographic measurements performed on 5- and 0.5-m resolution digital terrain models (DTMs) (respectively Regione Lombardia [ed. 2015], and Achille et al., 2022; Marotta et al., 2021) using System for Automated Geoscientific Analyses (SAGA) (Conrad et al., 2015) and QGIS 3.24 software. Based on the detailed DTM of the valley floor, channel network (CN) analysis (https://saga-gis.sourceforge.io/saga_tool_doc/2.2.4/ta_channels_0.html) was performed.

All the available chronological data were collected and attributed to the corresponding geological surfaces, sedimentary bodies and landforms. These include the archaeological findings from excavations, the known ages of historical buildings predating and postdating the 1618 landslide, radiocarbon age determinations from boreholes (Pigazzi et al., 2022) and data from literature (Tibaldi & Pasquarè, 2008).

The results of this part of the workflow are the following: (i) the 1:5000 map of the constraints to interpolate the geological surfaces composing the palimpsest landscape (stable, depositional or erosional), to be subtracted to one another to reconstruct the pre- and immediately post-1618 landslide topographic surfaces, and (ii) the landscape incremental history of the Piuro valley floor during about 1.5 ka BP.

To represent the increments of landscape evolution, the paleo-DTM of the topographic surfaces predating and immediately post-dating the 1618 landslide turning point was computed. The dataset was obtained drawing a series of 52 geological cross sections. In each of them, the two target surfaces were sampled by picking irregularly spaced points using a specifically designed script. Two *XYZ* point grids were obtained and used to interpolate the two surfaces by ordinary kriging using Surfer® code. The two resulting interpretations were displayed and analysed within QGIS 3.24.

The available iconographical and written documentation of Piuro was reviewed for comparisons between the proposed reconstruction and the traditional historical representations.

4 | BACK-STEPPING FROM THE PRESENT DAY TO THE PRE-1618 PIURO TOPOGRAPHY

The 1618 landslide provides an instantaneous and widespread marker of the landscape changes to be portrayed. Hereafter, the constraints used to trace-back the increments of landscape evolution from the present day back to the pre-1618 setting will be presented.

4.1 | Constraints to unravel the landscape evolution of the Piuro valley floor

After de-glaciation, the evolution of the Bregaglia Valley floor around Piuro was mainly controlled by alluvial and slope processes. The natural landscape of the study area (Figure 3) is formed by trunk river, debris-flow fans, landslide, slope and scree sedimentary bodies and related landforms.

Since 1618, the activity of the trunk Mera River and of its tributaries from the two sides of the valley contributed to rework the 1618 landslide morphologies, together with manmade interventions.

Four debris-flow fans build their sedimentary bodies into the main valley floor in competition with the Mera River. The largest one (Drana fan [DF]; Figure 3) progrades southwards from the North, constraining the Mera River course at the base of the opposite valley slope. Three minor debris-flow fans (Vallone Grande fan [VGF], Pigancione fan [PF] and Scilano fan [SF]; Figure 3) prograde northwards from the southern valley side.

Four depositional lobes related to secular avulsions of the Drana stream compose the present-day surface of the DF, numbered I to IV according to their younging (Figure 3). Each lobe shows an active deposition stage, represented by multiple individual debris-flow units formed by lobate bodies with a boulder-rich head, a cobble-rich tail and radially disposed crests. The low-discharge streams of each main lobe are entrenched into the debris-flow bodies along several abandoned stream gullies that may host thin gravel–sand torrential deposits. The surface sedimentary bodies of Lobe IV covered the northern reaches of the 1618 PL deposits (Figure 3) as it is documented by the physical stratigraphic relationships between the depositional units and by the contrasting facies, compositional features and provenance indications (Pigazzi et al., 2022).

Lobes I and II predate the 1618 PL, as they host the Sant'Abbondio settlement that is already mentioned in 16th century documents (Scaramellini et al., 1995) and the 16th century Vertemate-Franchi Palace (Benepiani, 1907; Figure 3A,B). A subsequent avulsion of the Drana torrent activated and started to feed Lobe III. The post-1618 activation of Lobe IV is testified by the flood that in 1755 destroyed the old church of Sant'Abbondio, of which only the bell tower remains (Figure 3B). This event plausibly occurred after avulsion of the Drana from its course along Lobe III to a new one on Lobe IV. Another evidence of the post-1618 activity of this latter lobe is the burial of some buildings close to the ancient church. Photos of the site, which was coincidentally unearthed in the 1980s and is no

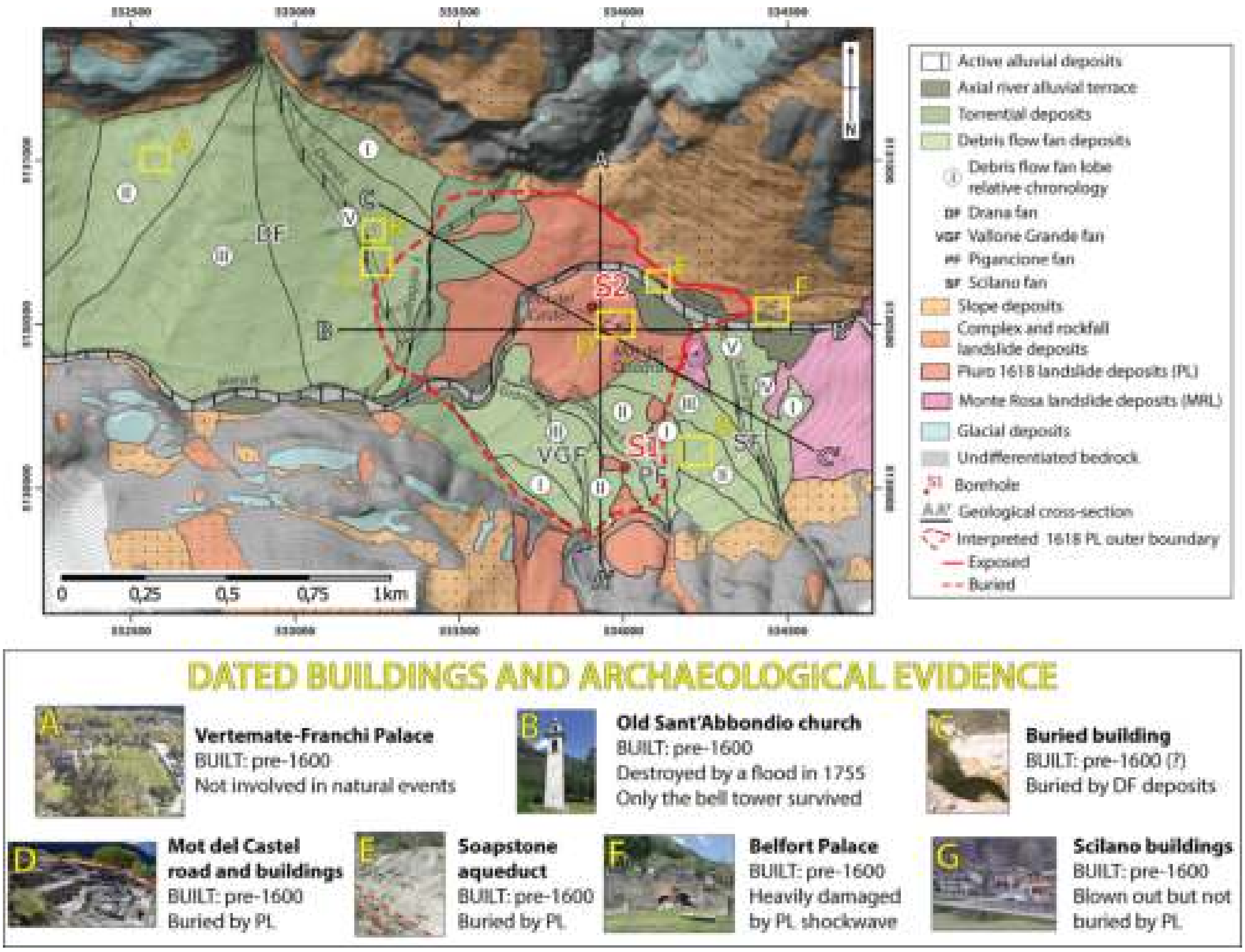

FIGURE 3 Geological map of the valley floor of Piuro. Yellow boxes indicate the location of dated buildings and archaeological findings, corresponding to the images below. Reported dates are AD. DF, Drana fan; PL, Piuro landslide.

longer accessible, show the ruins of a building within the present-day Drana thalweg buried by 4 m of multiple debris-flow sediments (Figure 3C), testifying the recurrent and large sediment discharge from the Drana torrent catchment.

Topographic and cadastral maps from 1811 to 1957 (Archivio di Stato di Milano, http://www.map.geo.admin.ch/) and aerial photographs from 1946 to present permitted to describe the changes of the hydrographic network on the DF during the last two centuries and the areas affected by the most recent flood events (Figure 4).

Drana torrent changed its course during the 19th century, sometimes splitting in two branches and temporarily reactivating abandoned valleys on Lobe III and on portions adjacent to Lobe I. Even if it was artificially stabilized in the present-day position, after 1900, it was still able to flood the middle and lower portion of the fan. CN on DF is controlled by the alternation of elongated humps and valleys developed after different debris-flow pulses, still clearly visible in undeveloped areas of Lobes III and IV. Incised valleys are still well preserved on Lobes I and III, according to the courses indicated by historical maps. It derives that Lobe IV was active at least since the second half of the 18th century, with several avulsions of the Drana stream until its manmade stabilization. Immediately East of DF, the Acquafraggia torrent remained almost stable in its present-day position since 1811, when the torrent split in two streams. CN analysis shows the multi-stream hydrographic network and the associated fan morphologies, in good match with the pictures derived from maps and aerial photographs (Figure 4).

The course of the Mera River has not changed significantly over the past two centuries, deepening in its position, especially after the building upstream of the Villa di Chiavenna dam in 1949. The present-day course crosscuts and erodes the PL deposits. Two orders of narrow terraces of sandy gravels flank and locally cover the PL bodies. Rounded, polygenic cobbles and boulders with minor sand mainly compose the sediments within the riverbed. Among them, metric to pluri-metric angular boulders of migmatitic gneiss, amphibolite and ultramafite belonging to the Gruf Complex and Chiavenna Unit remained unremoved in the riverbed, as large-scale lags of the 1618 landslide body (Figure 5).

The component depositional lobes have been also mapped in the three southern debris-flow fans (VGF, PF and SF from W to E; Figure 3). Every lobe preserves in its upper portion boulder bodies with radial crests separated by elongated depressions, representing individual debris-flow bodies and the intervening gullies. These morphologies smooth out towards the distal portions of the fans, due to progressive reduction in the grain size of deposits and anthropogenic reworking. S1 borehole (Figure 6) shows a landslide body sandwiched in between the deposits of the recent Pigancione Lobe II (Figure 3) and another underlying debris-flow fan. Radiocarbon ages constrain this latter to predate the 1618 PL by several decades (Figure 6) and

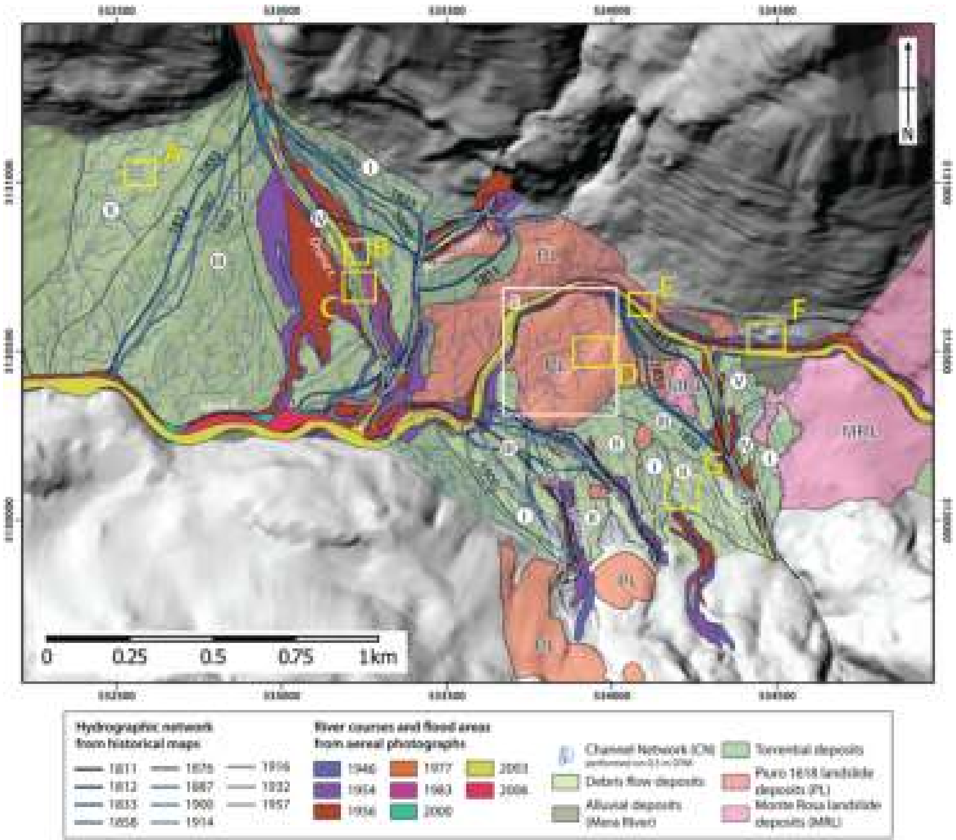

FIGURE 4 Evolution of the hydrographic network during the last two centuries, based on analysis of historical maps and aerial photographs and on the channel network (CN) analysis performed on 0.5-m digital terrain model (DTM). Box a indicates a small valley incised within Piuro landslide (PL) deposits, discussed later in the text. Yellow boxes indicate the location of dated buildings and archaeological findings as reported in Figure 3.

FIGURE 5 The present-day Mera riverbed carved within the deposits of the 1618 Piuro landslide (PL) in the central portion of the ancient Piuro. The boulders highlighted in colours are lags from the PL body. Buildings in the background were built on the top of PL deposits.

confirm that the overlaying landslide deposit corresponds to the 1618 event. The slight reversal of radiocarbon ages in the buried stratigraphy is related to exhumation and redeposition of progressively older materials by the sliding events through time.

Between Lobes I and II of PF, two small morphological highs fingerprinted by the lithology of boulders as part of the PL body arise (Figure 7). CN shows that these humps were partly eroded and isolated by the Pigancione and Scilano torrents (Figures 4 and 7). These data indicate that PL partly covered the lobes that were active at that time and was successively buried and eroded by VGF I–II, PF I–II and SF III fan lobes (Figure 7). The geomorphological and stratigraphic relations mapped in Figure 6 also show that SF Lobes IV and V postdate the 1618 event. Instead, Lobes I and II of SF appear to predate the 1618 landslide. Lobe I directly covers the Monte Rosa landslide (MRL), a huge boulder body slid from the northern valley slope, at present exposed East of Mot del Castel (MC) (Figures 3 and 7; Pigazzi

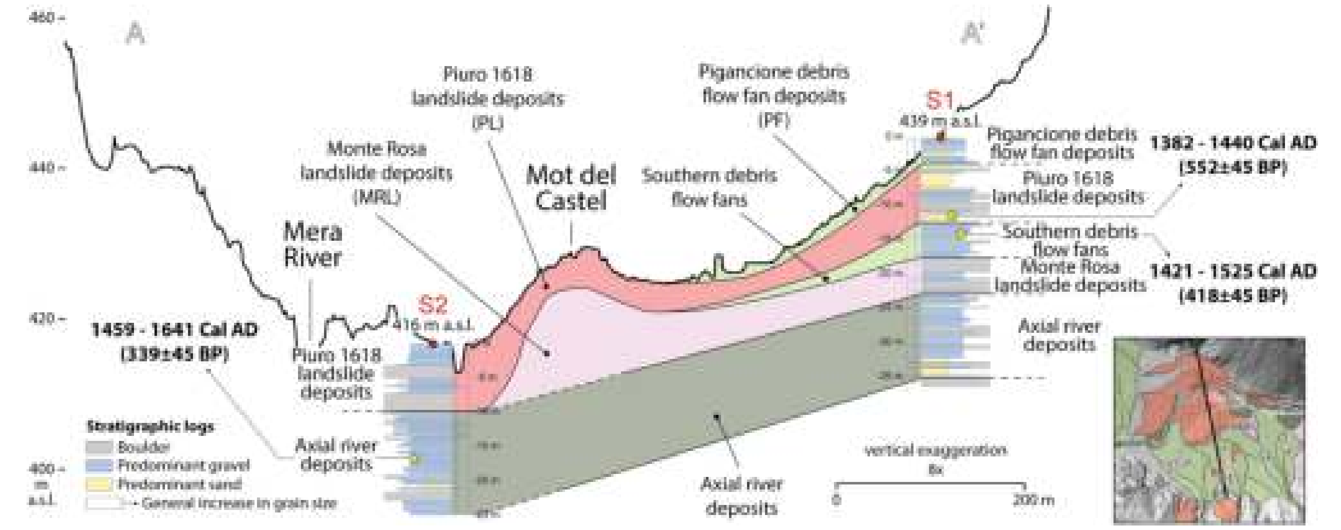

FIGURE 6 Stratigraphic logs and correlation between S1 and S2 boreholes. Location of the cross section in the right-hand insert. Relative stratigraphic positions and radiocarbon ages determinations have been reported (analyses performed at CEDAD Lab—University of Salento).

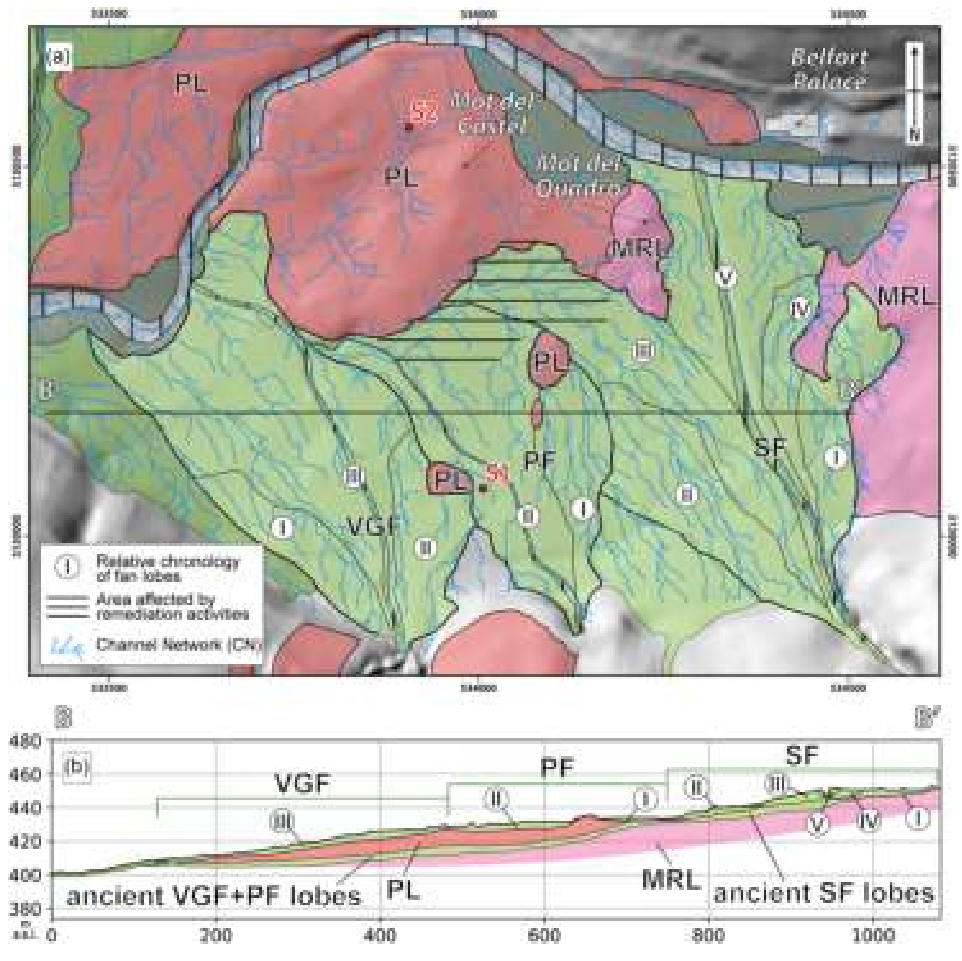

FIGURE 7 (a) Surface and sub-surface geomorphological and stratigraphic relationships at the southern side of the study area and channel network (CN) distribution on the southern debris-flow fans. Same legend of geological units as in Figure 3. The area South of Mot del Castel and Mot del Quadro has been strongly reworked and remediated. (b) Cross section BB′ shows the sub-surface relations between the lobes of the alluvial fans (VGF, Vallone Grande fan; PF, Pigancione fan; SF, Scilano fan) and the two landslide bodies (MRL, Monte Rosa landslide; PL, Piuro landslide). Note the decreasing elevation of the top fan surfaces from SF (East) to VGF (West), reflecting the westward dip of the top of the underlying MRL body.

et al., 2022). Lobe II was the site of the ancient Scilano settlement, whose existence is reported by historical documents (Scaramellini et al., 1995; Figure 3G). Chronicles of the time refer that the 1618 landslide destroyed this ancient nucleus, more likely because of the shockwave rather than its burial.

The analysis of historical maps (Figure 4) shows that the course of Vallone Grande torrent changed between 19th and 20th centuries and then remained stable since 1932. Pigancione torrent course remained almost stable, except for its confluence with the Mera River. Scilano torrent changed its course from 1811 to 1833, stabilizing after 1900. Considering that this portion of Piuro was primarily exploited for vineyards and pasture fields, it is likely that these streams have been repeatedly channelled over time, changing their courses. CN distribution seems overall to delineate the paths of the streams that run the southern lobes, apart for Lobe I of the SF. In fact, minor hydrographic network developed on this lobe appears to be partly inconsistent with any morphologies referable to the Scilano torrent (Figure 7), supporting the interpretation of SF I as an ancient and reworked body.

The top surface of the southern fans shows a systematic dip from East to West, with the apex of the SF raising up to 40 m above the one of the Vallone Grande fan. The stratigraphy of S1 borehole (Figures 6 and 7) shows that a landslide body underlays the southern debris-flow fan deposits. Its provenance from the northern valley slope was demonstrated by the lithology of boulders, leading Pigazzi et al. (2022) to correlate this body to the exposed MRL. Hence, the general westward dip of the southern fans might relate to the westward sloping of the top of MRL body away from the slide-scar.

The former data indicate that the deposits of the 1618 PL and their morphologies have been partly covered by debris-flow fans from both the valley sides, eroded by streams and partially reworked by anthropic activity. The remnants are still exposed around the modern Piuro.

The expansion of PL deposits in the valley bottom caused the temporary damming of the Mera River in the Belfort area, as reported by historical documents (Scaramellini et al., 1995, with references). Consequently, the building was buried by about 5 m of alluvial gravel and sand deposits (Figure 8) of the Mera River and Scilano torrent, as shown by archaeological excavations conducted in this area (Breda et al., 2014).

After erosion, PL deposits were flanked by the Mera alluvial terraces before the incision of the present-day riverbed (Figures 3 and 4). The CN analysis shows that a southwestward drainage started to develop probably at the same time above the PL body, as it is exemplified by the small valley shown in Figure 4, Box a.

PL body partially covered the MRL deposits, as it is observed at Mot del Quadro (MQ) (Figures 3 and 7). Within the archaeological site of MC, remains of buildings and a section of a road were discovered just underneath the sandy–loamy gravels with boulders of PL (Maurizio, 1972; Schneider, 1964; Zaugg, 1967), testifying the burial of this area in the 1618 event. The disposition of these buildings, the presence of anthropogenic terraces and the slope of the road indicate that this portion of the ancient village was effectively built above a pre-existing relief. Metric angular boulders of gneiss consistent with a northern provenance emerge among the buildings at the site, in some cases utilized as structural elements. These observations confirm that the MC relief pre-existed PL, most likely representing the westernmost reach of MRL. The oldest settlements discovered to date on this relief date back to the 4th – 7th century AD (Saggioro, personal communication, 2021) constraining the MRL deposits at least to predate this age. A post-glacial age is indicated by the lack of glacial reworking.

In borehole S1, South of MC, MRL deposits cover the trunk river gravels and sands (Figure 6). The stratigraphy of borehole S2, where the MRL body is not present (Figure 6; Pigazzi et al., 2022), suggests

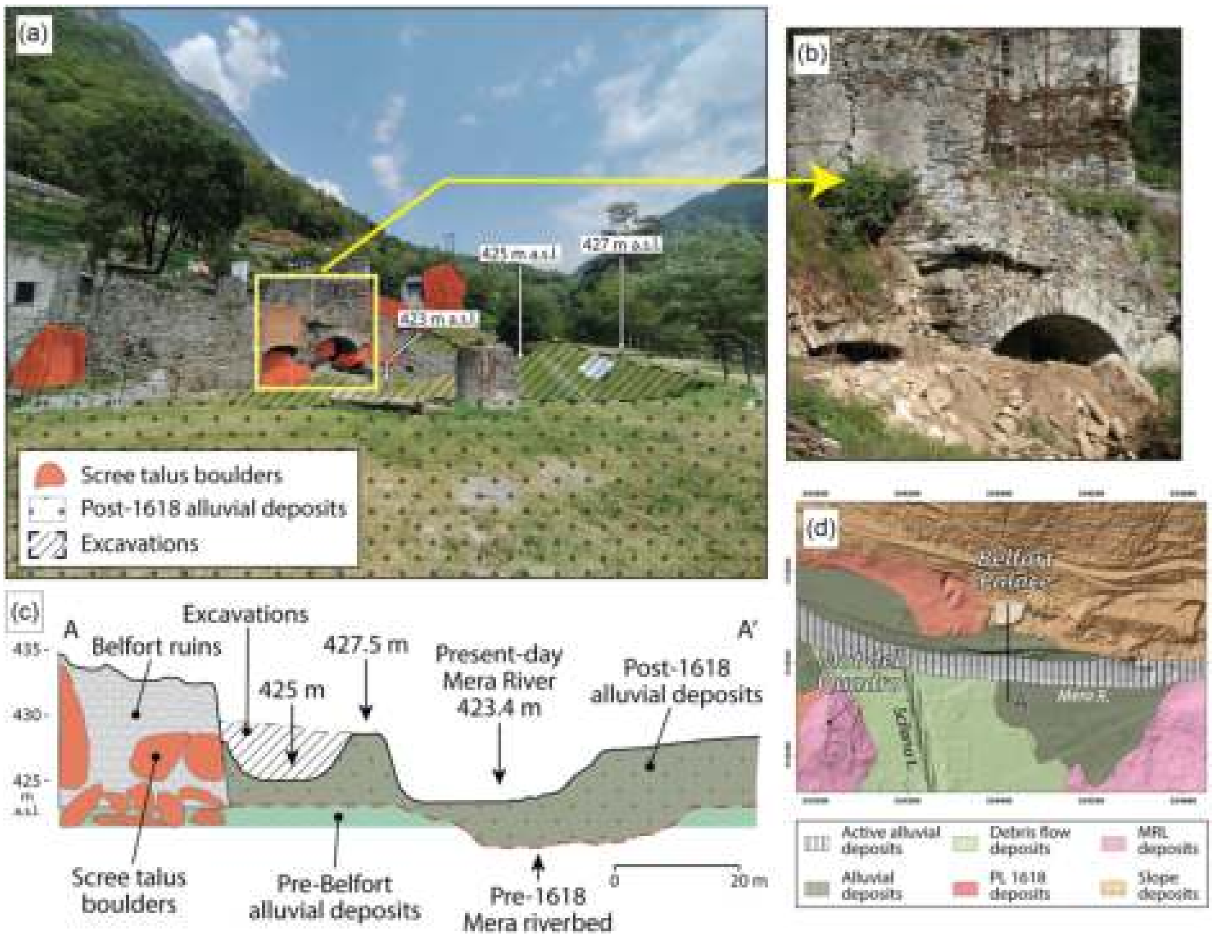

FIGURE 8 (a) The ruins of Belfort Palace built at the foot of the northern base of slope deposits composed by metric boulders. The excavations conducted in 2014 permitted to reach the base of the edifice covered by up to 5 m of alluvial deposits (b) after the barrage created by the 1618 landslide. Cross section AA′ reflects the geological setting of this area (c). Location of cross section in (d).

TABLE 1 Relative chronology of the increments of landscape evolution of the Piuro area.

Lithosome	Type of deposits	Relative chronology
Axial river deposits (Mera River)—Second-order terraces	Alluvial/torrential	Post-1618
Axial river deposits (Mera River)—First-order terraces	Alluvial/torrential	Post-1618
DF—Lobe IV; VGF—Lobes I–III; PF—Lobes I and II; and SF—Lobes IV and V	Debris flow	Post-1618
SF—Lobe III	Debris flow	Pre- to post-1618 (?)
DF—Lobe III	Debris flow	Pre- to post-1618
PL	Landslide	1618
Buried VGF and PF (S1 borehole)	Debris flow	Post-MRL
DF—Lobe II	Debris flow	Post-DF—Lobe I/pre-16th-century AD
SF—Lobe II	Debris flow	Post-SF—Lobe I/pre-1618
DF—Lobe I	Debris flow	Post-LGM/pre-Sant'Abbondio settlement (?)
SF—Lobe I	Debris flow	Post-MRL
MRL	Landslide	Post-LGM/pre-4th- to 7th-century AD
Axial river deposits (S2 borehole)	Alluvial/torrential	Post-LGM/pre- to post-MRL
Axial river deposits (S1 borehole)	Alluvial/torrential	Post-LGM/pre-MRL

Abbreviations: DF, Drana fan; LGM, Last Glacial Maximum; MRL, Monte Rosa landslide; PF, Pigancione fan; PL, Piuro landslide; SF, Scilano fan; VGF, Vallone Grande fan.

that as a consequence of this landslide, the trunk river deposition moved beyond its farthest reaches, to North and West. The mentioned 4^{th} – 7^{th} century AD settlements at MC could develop on this relief during the time bracket between the MRL and PL events that hence are separated by at least 1.5 ka. This conclusion is reinforced by the 15^{th} to 16^{th}century radiocarbon age of the axial river deposits sampled below PL in borehole S2 (Figure 6), which indicate the position of the trunk river just before the 1618 catastrophe.

The stratigraphic, morphological and chronological constraints here presented permit to sketch the relative chronology of increments of landscape evolution of the Piuro valley floor. It is summarized in Table 1, back-stepping from the present day.

4.2 | Reconstruction of the ancient Piuro pre- and post-1618 landslide topography

To reconstruct the pre- and post-1618 topography of Piuro, 52 cross sections were drawn through the area, 16 of which focus on the PL exposures. We considered also the areal extent of PL as contoured by Pigazzi et al. (2022). The thickness of this body was checked at the two borehole sites (8.5 m in S1 and 10 m in S2) and at the archaeological sites of MC (3–4 m) and Belfort (3–6 m; Figure 7).

Further considerations on the depth of deposits were utilized as constraints drawing the cross sections: (i) The Mera River is still cutting PL deposits, indicating a depth of at least 8 m with respect to the present-day river banks (Figure 5); (ii) the finding of a tract of a soapstone aqueduct dated back to at least the 17^{th} century along the right Mera bank excavations (Associazione Italo-Svizzera per gli Scavi di Piuro, 2013) (Figure 3E) suggests that the pre-1618 riverbed was deeper than the present-day one and in a different position; (iii) an average thickness of 3–4 m for VGF and PF was observed at S1 and at an excavation near the borehole; (iv) a thickness of 4–10 m is likely for the deposits of Lobe IV of DF considering the buried building near the ancient Sant'Abbondio church (Figure 3C); (v) considering the erosion by the southern streams and the anthropic reworking of the area, at least 2–3 m of deposits have been removed in the portion between the two elongated humps of PL and the morphological highs of MC and MQ (Figure 7); and (vi) the progressive urbanization of the new centre of Piuro flattened the morphologies of the top of PL deposits. The sum of these observations integrates the geological map of the lower boundaries of the different lithosomes, permitting to interpret the stratigraphy in all the profiles with an acceptable degree of uncertainty. In each of them, the two pre- and post-1618 PL topographic surfaces (blue and red dotted lines respectively in the cross sections of Figure 9a) were identified using the following: (i) the preserved and unmodified top of the sedimentary bodies that predate the 1618 combined with the base of PL to delineate the best approximation of the topographic surface of the pre-1618 landscape (pre-1618 topography); (ii) the preserved top of PL deposits combined with the base of the sedimentary bodies by which they were buried to delineate the topographic surface immediately after the 1618 event (post-1618 topography); and (iii) the map of post-1618 erosional surfaces. Where eroded, the top of PL deposits was interpreted by interpolating the preserved exposures and accounting for remodelling due to the urbanization of the area. From each profile, a series of *XYZ* points have been extracted along the lines representing the pre- and post-1618 topography (Figure 9C), while for the areas considered stable since 1618, a *XYZ* point grid has been extracted from the present-day DTM.

Combining these with all the other control points resulted in two different point grids that were used to calculate the two paleo-DTMs by ordinary kriging (Figure 10).

Considering the large spacing of the data points and the intrinsic uncertainties, only the large-scale topographic features can be considered fully reliable. Among them, the course of the Mera River appears consistent with the constraints proposed above. For instance, the representation of the 1618 river course is comparable to the present-day one around Belfort Palace, as it was expected owing to the stable physical constraint provided by the MQ hump. The river had to flow South and deeper than the mentioned aqueduct section (Figure 3E); otherwise, it would have intersected the artefact. Westwards, the

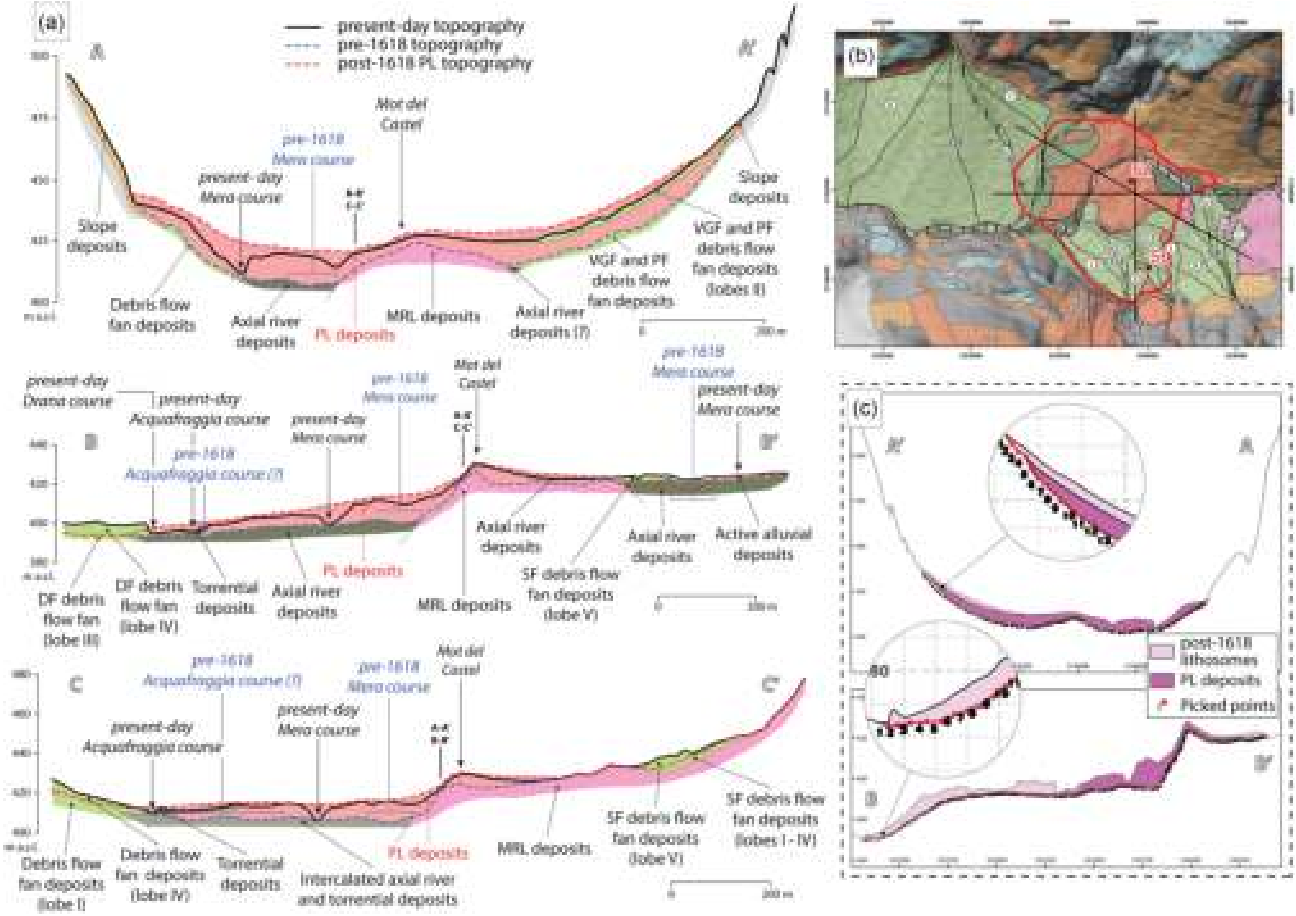

FIGURE 9 (a) Three selected cross sections used to compute the pre- and post-1618 paleo-digital terrain model (DTM) of the study area. Black thick line represents the present-day topography, blue dashed line the pre-1618 topography and red dashed line the post-1618 topography. (b) Location of cross sections (see also Figure 3). (c) Examples of picking of points to compute the paleo-DTM of the pre-1618 surface in sections AA′ and BB′.

present-day riverbed cuts its way through PL deposits, in a different and elevated position with respect to the ancient one (Figure 10c). The pre-existing MC relief constrained the river to run just North of it, as it is represented by the computed paleo-DTM. In fact, according to archaeological and electromagnetic surveys (Schneider, 1964) and oral tradition, the main bridge of the ancient Piuro should have been close to S2 borehole (Figure 7). The road chunk found during archaeological excavations (Figure 3D) would have plausibly connected the settlements of MC with this bridge. These considerations suggest that the ancient Mera flowed around this position (roughly in S2) and then deviated to the Southwest probably following the northern flank of the morphological high of MC, as it is represented by the pre-1618 paleo-DTM (Figure 10c). The 1618 landslide body covered and regularized the former morphology, burying the MC high and the ancient Mera riverbed. Consequently, the thickness of PL increases from 3 to 4 m at the MC to 10 m in S2 borehole with a difference in height up to 14 m, supporting the mentioned pre-1618 location of the Mera thalweg. The analysis of S1 borehole data showed that the southern debris-flow fans (VGF and PF; Figures 3, 6 and 7) remained confined South of MC and MQ humps. The courses of the Vallone Grande, Pigancione and Scilano low-discharge streams are not clearly represented by the pre-1618 DTM. The paintings of the ancient Piuro and recent archaeological evidence (Saggioro, personal communication, 2021) suggest that this area was exploited for vineyards, pastures and crops, so it is likely that the streams were conveyed into the Mera River Southwest of Piuro. The ancient low-discharge stream of the SF flowed plausibly North of the Scilano settlement, on SF Lobe III. The stream joined the Mera River more likely westward of Belfort Palace (Figure 10c) than South of it, where the present-day confluence is a recent artefact. To the North, the 1618 PL barred and deflected westwards the Acquafraggia course to its current position. West of it, the low-discharge Drana stream run through DF Lobe III, thus was not directly involved in the landslide (Figure 10c). The subsequent progradation of Lobe IV buried the north-westernmost reaches of PL deposits.

After the disaster, several artists depicted the landscape around Piuro both before and after its destruction. In many cases, these paintings were based more on imagination than on true observations (Scaramellini et al., 1995). The most detailed and somehow reliable painting of Piuro is preserved and exposed at Vertemate-Franchi Palace (Figure 11) by an unknown artist of the 17th century, painted after the destruction of the village. The comparison with the paleo-DTM and chronological landscape evolution permits some observations.

In the painting (Figure 11), the Vertemate-Franchi Palace (1), the ancient church of Sant'Abbondio with the recently unearthed annex buildings (2), the Belfort Palace (3), the Scilano (4) and Sant'Abbondio (5) settlements and the main bridge of Piuro (6) are located in

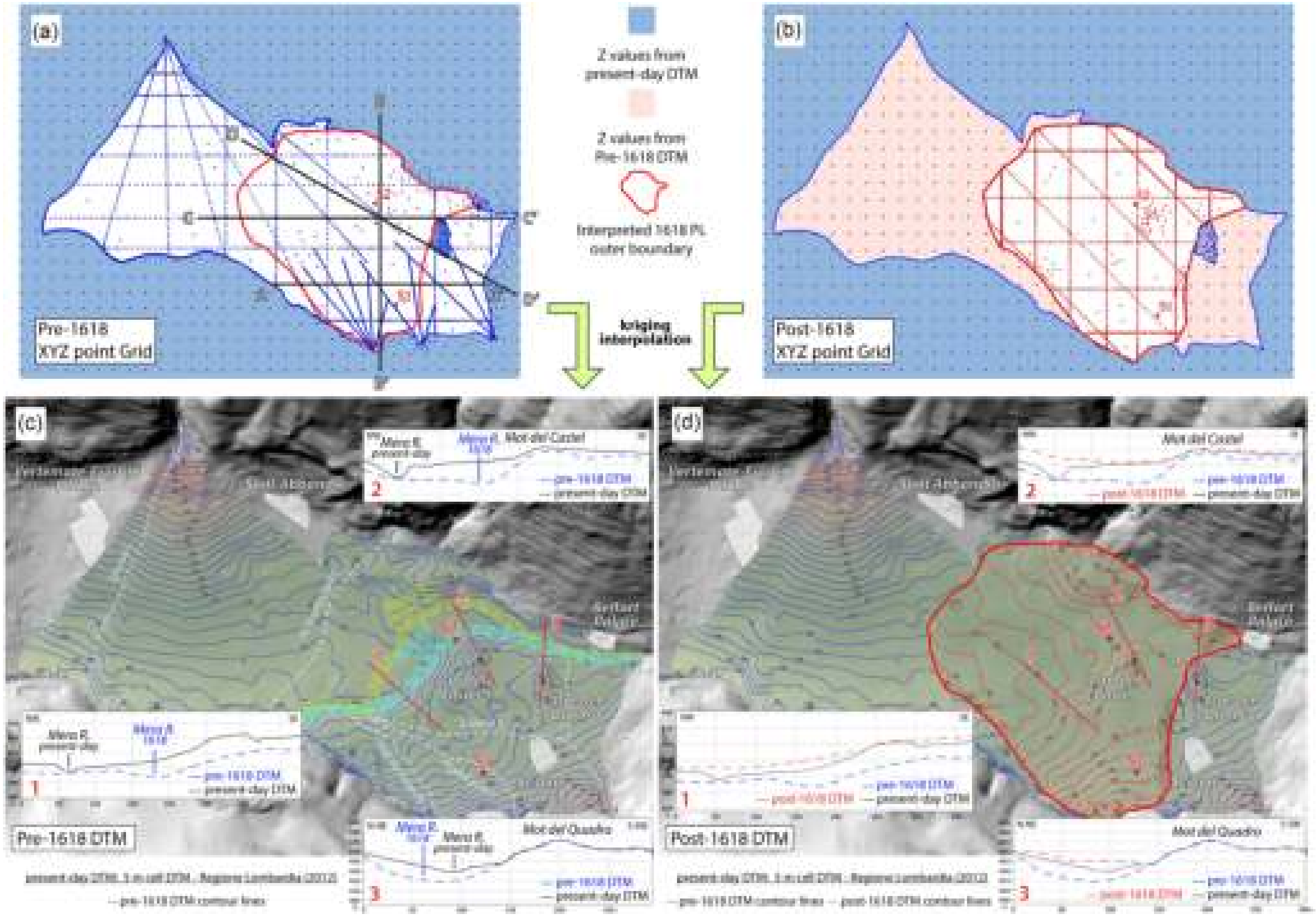

FIGURE 10 (a, b) The *XYZ* point grids used to compute the pre-1618 and the post-1618 surfaces. White areas contain the points picked from geological cross sections; *Z* values of the points within blue areas coincide with the *Z* value of the present-day digital terrain model (DTM), as considered stable areas since 1618; points within red areas were used for the post-1618 reconstruction, and their *Z* values coincide with that of the pre-1618 DTM. (c) Pre-1618 DTM and (d) post-1618 DTM obtained after ordinary kriging of the data points (grey areas are considered not appreciably varied since 1618 and thus coincide with the present-day DTM). Topographic Profiles 1–3 in (c) and (d) permit to compare the two obtained surfaces with the present-day topography.

FIGURE 11 A 17th century painting of Piuro before its destruction, exposed at Vertemate-Franchi Palace. Enlighted edifices and architectural elements are discussed in the text. 1—Vertemate-Franchi Palace; 2—old Sant'Abbondio church and annex buildings; 3—Belfort Palace; 4—Scilano; 5—Sant'Abbondio settlement; 6—main bridge of Piuro.

somehow realistic relative positions (compared to Figure 3). The course of the Mera River between the Belfort Palace (3) and the ancient bridge (6) would not differ so much from the present day. Differently, the Acquafraggia and Drana torrents present own confluences with the Mera River in the painting. The Drana torrent is represented close to Vertemate-Franchi Palace, hence on Lobe III of DF,

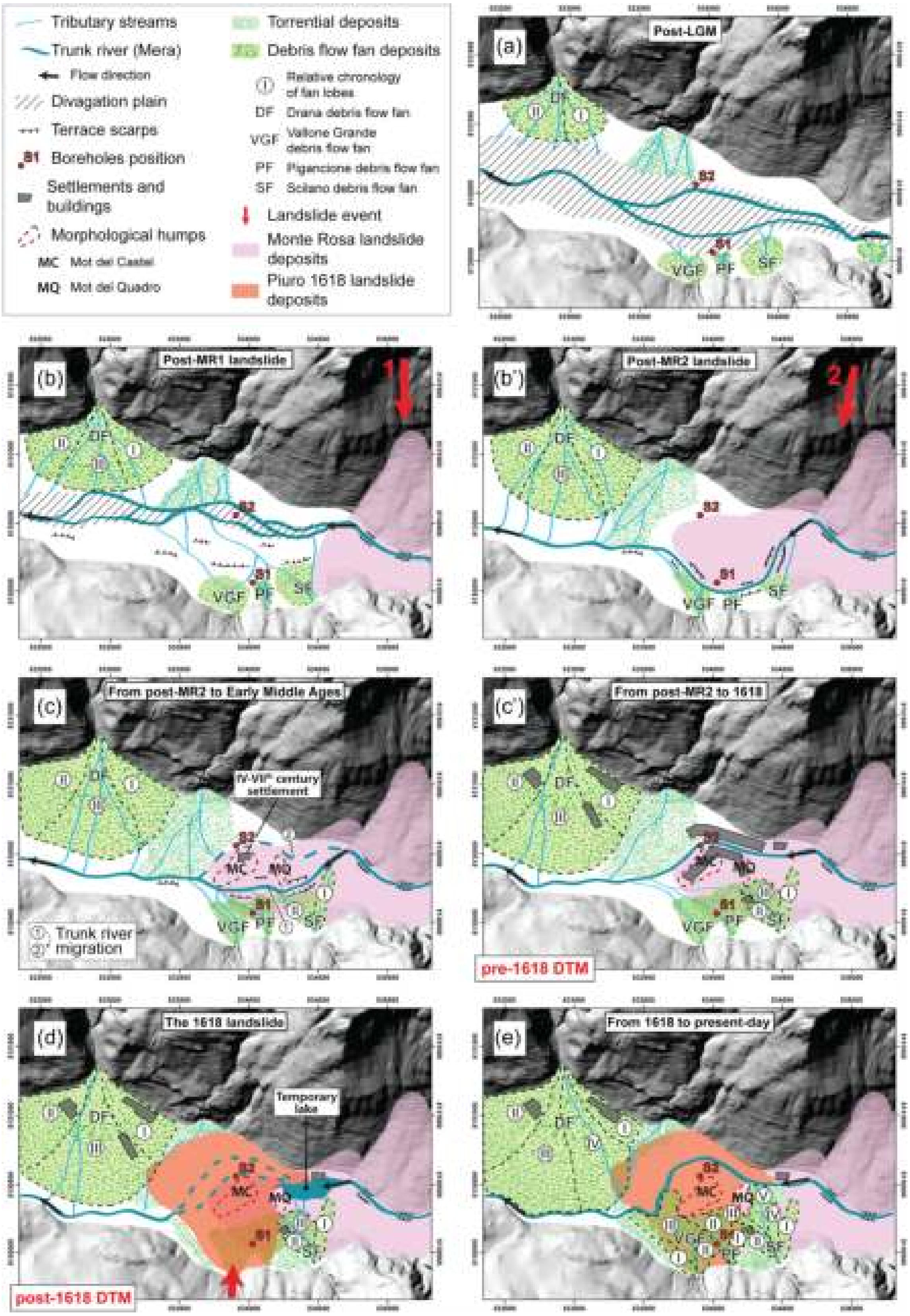

FIGURE 12 Most relevant increments in the geological evolution of the Piuro area. (a) The valley floor after the Last Glacial Maximum (LGM) de-glaciation, widely occupied by the trunk river. (b) The first episode of the Monte Rosa landslide (MRL) that forced the northward diversion of the trunk river. (b′) The second MRL event expanded westward, forcing the trunk river to divert southward. (c) Mot del Castel (MC) and Mot del Quadro (MQ) humps are outlined as a result of erosion of the trunk river. Settlements started to develop on top of MC since Late Roman–Early Middle Ages. (c′) The position of the trunk river settle down North of the MRL humps. Settlements gradually spread over stabilized lobes and nearby areas until reach the 1618 configuration of the ancient Piuro, drawn in the pre-1618 digital terrain model (DTM). (d) The 1618 landslide sealed the oldest landscape. Mera River was temporary dammed but progressively carved its path into the landslide deposits. The post-1618 scenario is depicted in the post-1618 DTM. (e) The progradation of the debris-flow fans continued until partially covering the 1618 landslide deposits following the relative depositional chronology described earlier, until reach the present-day configuration.

consistently with the paleo-DTMs in Figure 9. From the southern valley slope (right side of the painting), two streams reach the valley bottom and turn abruptly towards southwest of the Scilano settlement (4), following the base of the slope (Scilano torrent to the left and perhaps Pigancione torrent to the right). Differently, the manmade present-day course of Scilano reaches straight the Mera River opposite to the Belfort area (Figure 3). The westward flow of the streams looks to be in keeping with the general westward dip of this area, owing to the deposits of the MRL, which is still maintained today. This image might imply also that the sharp diversion of the same streams was manmade to protect the southern part of the village and the crops from flooding.

5 | SUMMARY AND DISCUSSION

The evolution of the Piuro landscape can be summarized on a secular timescale by a sequence of increments predating and postdating the 1618 landslide turning point. Similar approaches already proved useful to decipher paleo-landscapes in different settings linked to human activities, such as alluvial plains (e.g., Bertacchini, 2009; Ferrario et al., 2015; Forti et al., 2020; Schmidt et al., 2018), coastal areas (e.g., Westley et al., 2014), debris-flow fans (Colombera & Bersezio, 2011), Alpine valleys affected by large historical landslides (e.g., Marcolla et al., 2018; Scapozza et al., 2015) and peri-glacial domains (e.g., Scapozza et al., 2021). The backward subtraction of the individual sedimentary bodies and landforms under chronological and geometrical constraints permitted to compute the DTMs of the paleo-landscapes before and after the catastrophe.

5.1 | Secular evolution of the post-glacial Piuro landscape

The scenario depicted in this study shows that since the retreat of the Engadine Glacier, the entire valley floor around the future Piuro was occupied by the Mera trunk river in competition with the lateral debris-flow fans. Two catastrophic events, the Monte Rosa and the 1618 PL, affected the area, imposing to decipher the history of landscape evolution before, between and after them. The most relevant increments of this history will be presented hereafter with the help of the maps in Figure 12.

5.1.1 | The landscape predating the MRL

Before the post-glacial MRL event, the Mera trunk river occupied widely the Piuro valley floor (Figure 12a), as documented in S1 and S2 wells. Debris-flow fans had started growing from both the valley slopes since the de-glaciation. From the North, DF Lobes I and II, flanked by the Acquafraggia torrent bodies, interfingered with the braided Mera River, which was free to migrate across the valley floor. The small lobes of the southern fans could not reach the valley axis. At this time of the landscape history, geomorphological stabilization could occur only on the surfaces of the temporarily inactive fan lobes and/or abandoned trunk river courses, on a decadal to secular timespan.

5.1.2 | The MRL events

The oldest traces of human settlements sitting above the MRL reliefs date from the 4th – 7th century AD, so this event must be older than these findings. Because there are no chronicles of this catastrophe even in the latest Roman times, the MRL plausibly predates the Roman age. It barred the valley, with an estimated volume of 20 Mm^3, sliding from the northern flank and remounting the opposite foot-slope. The event might have occurred in two separate episodes, widening the same landslide scar (MR1 and MR2 in Figure 12b,b′), so explaining the westward reaches of the boulder deposits. There is no tight age constraint for the two slides that remain bracketed between post-de-glaciation and pre-Roman times. However, considering the limited thickness of the alluvial deposits burying the MRL, a historical age looks to be likely for this event. The landslide widely reshaped the valley floor, building several humps raising by tens of metres above the alluvial floor of the valley centre. The Mera trunk river was forced to bypass the first boulder body, building upstream an alluvial ramp and lately finding a way close to the northern slope (Figure 12b). After the second slide, the trunk river was pushed southward. The growth of the southern debris-flow fans was therefore suffocated, while the northern and larger ones (i.e., DF) could prograde more freely southwards (Figure 12b′). River erosion re-modelled the southern portion of MRL deposits, contributing to shape the isolated humps.

5.1.3 | From MRL to the 1618 Piuro catastrophe

After the second MRL event, Lobe I of SF started to prograde over the MRL hump to the North (SF in Figure 12c), contributing to the progressive northward migration of the Mera trunk river that carved the southern flank of MC and MQ humps (Figure 12c) and partly buried the landslide deposits. DF Lobe III prograded southwards during the progressive migration of the Mera River that moved to the North of the MRL humps. This diversion was already accomplished in the 1618 setting, as it is documented by the mentioned geological and archaeological data and by historical paintings. The few stable surfaces existing on a decadal to secular timescale during this increment of landscape history are documented by some neither eroded nor buried remnants, as mapped in Figure 3. These settings were progressively occupied starting from the most elevated ones in the oldest times. The human settlements dating back to Late Roman–Early Middle Ages occupied the elevated and sheltered positions offered by MC hump. Successive urbanization continued on the abandoned and stabilized debris-flow fan lobes, such as Lobes I and II of DF (Sant'Abbondio and Vertemate-Franchi Palace) and Lobe II of SF, until the development of the opulent Piuro, as it was known at the beginning of the 17th century (Figure 11).

5.1.4 | The 1618 PL

In the evening of 25 August 1618, according to the Julian calendar, at present corresponding to 4 September, the landslide detached from the head of Vallone Grande on the southern side of the Bregaglia Valley wiped out Piuro, causing at least 1000 casualties. The landslide completely reshaped the valley floor, covering most of the MRL

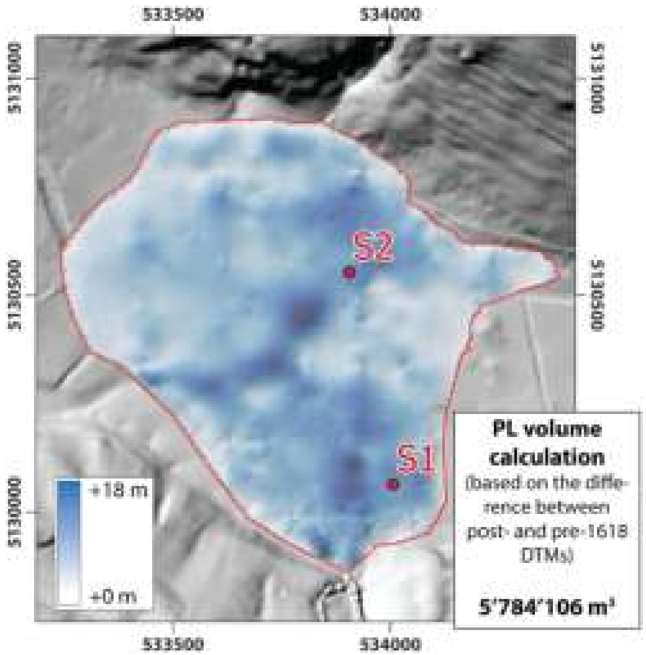

FIGURE 13 Estimate of volume of Piuro landslide (PL) deposits on the valley floor, obtained by subtraction of the pre-1618 digital terrain model (DTM) from the post-1618 paleo-DTM.

humps, parts of the Mera River course and of the debris-flow fan lobes (Figure 12d), representing a turning point in the landscape evolution of the area. The previous topography controlled the landslide deposition. The MQ hump sheltered the Belfort Palace, deflecting the sliding mass that still managed to climb the northern valley slope. Due to the mentioned general westward slope of the southern valley side determined by the dipping top of the MRL bodies, the 1618 moving mass expanded to the West, brushing against the DF toe.

By subtracting the obtained pre-1618 DTM from the post-1618 one, we could calculate a volume of ca. 5.8 Mm^3 for the 1618 landslide deposits in the valley bottom (Figure 13). Considering an estimated >1 Mm^3 of material still preserved on the slope (Pigazzi et al., 2022), a total volume of about 7 Mm^3 might be figured out, which is consistent with the former estimate (Morcioni et al., 2023; Pigazzi et al., 2022).

5.1.5 | From 1618 PL to present

The 1618 landslide instantaneously covered and sealed the previous landforms. The chronicles and paintings report that the Mera River was dammed forming a temporary lake, which overpassed the barrier without additional damages within few days or even hours. This barrage caused the partial burying of the Belfort Palace (Breda et al., 2014) (Figure 12d) and of the other bank. The Mera River then started to carve its path through PL deposits and underwent several manmade interventions until it reached its present-day position (Figure 12e). The southern debris-flow fans started to prograde over the landslide deposits following the mentioned relative depositional chronology (Table 1). The progressive reclamation of this area since the 19th century led to channelization of the streams and stabilization of the old fan lobes and to reworking of the southern side of MC and MQ (Figure 7). Lobe III of DF continued to prograde until the 17^{th} to 18^{th} century avulsion of the stream that activated Lobe IV, leading to the destruction of the old Sant'Abbondio church and the burial of the westernmost portion of the PL body. Drana torrent has been repeatedly channelized since the 19th century, permitting to Lobes I and II to remain stable as proved by the preservation of the buildings they host. Sporadic flood episodes involved Lobes I and III, as documented by historical maps and aerial photographs (Figure 4). In addition to stream regulation works, the reconstruction of the Piuro village contributed to smooth the landforms of the landslide body over large areas.

5.2 | Controls on landscape evolution in the Central Alps around Piuro

Since the de-glaciation, the Bregaglia Valley evolved from peri-glacial to non-glacial conditions. The de-glaciation steps are documented by several observations. At the Swiss–Italian border, not far from Piuro, the base of an alluvial sequence that covers and erodes an LGM frontal moraine in the valley bottom has been dated to 15 ka BP (Pasquarè, 2001; Tibaldi & Pasquarè, 2008). A few kilometres East, a decrease in cold glacial and snow meltwater feeding the Upper Engadine lakes is registered around 13.7 ka cal BP (Gobet et al., 2003; Ilyashuk et al., 2009), followed by the Younger Dryas cold phase between ca. 12.85 and 11.65 ka cal BP and then by an abrupt reversion to warmer temperatures during the Holocene (Ilyashuk et al., 2009). During the Younger Dryas stadial, glacial advance remained confined to altitudes greater than 1900–2000 m a.s.l. in the Engadine Julier Pass (Ivy-Ochs et al., 1999), while the de-glaciation of the Splügenpass (ca. 2100 m a.s.l., NW of the study area) was already completed, as it has been dated around 18.99–13.53 ka b2k (Scapozza et al., 2021).

Glacier expansion during the Younger Dryas thus appears to have been discontinuous and restricted to altitudes around or above 2000 m a.s.l. in this sector of the Central Alps. This means that peri-glacial conditions inducing rhexistasy contributed to the erosion of the upper–medium portions of the slopes. The sudden Holocene increase in temperatures has plausibly led to the progressive thawing of permafrost, a known trigger factor for slope instability (e.g., Dramis et al., 1995). The weakening effect of thermally induced perturbations on the mechanical behaviour of rock masses (Li & Shao, 2016) was found, in addition to glacial debuttressing after LGM (e.g., Cossart et al., 2008), as one of the main predisposing factors for another historical landslide in Cimaganda (Morcioni et al., 2022), ca. 9 km NW of Piuro, dated 900 AD (Mazzoccola, 1993) (Figure 1c).

The Little Ice Age (LIA—Grove, 1988; Moss, 1951; Porter & Denton, 1967), which spanned 400–500 years between 15^{th} and 19^{th} centuries (Bradley & Jones, 1993; Jones et al., 1998; Mann et al., 1998, 1999), even if geographically discontinuous brought to general colder temperatures and altered weather conditions, inducing widespread glacial advances throughout the Alps (Mann, 2002). Evidence of LIA glacial increases has been found not far from the Piuro area, always confined above 2000 m a.s.l. (Tantardini, 2016; Tantardini et al., 2022). Within the overall cold phase of the LIA, climatic fluctuations led to alternating relatively warmer and colder climatic anomalies (Bradley & Jones, 1993), accompanied by alternating severe floods, drought and frost episodes documented throughout the mountain regions of the Mediterranean Europe (Grove, 1988).

This variability may have resulted in local oscillations of permafrost limits in the upper portions of the slopes on a decadal scale. As discussed above, the combined effect of cyclic temperature variations and glacial advances and retreats enhanced the progressive mechanical degradation of the rock masses. Coupled with the geological and structural peculiarities of the slopes, it is possible that this has led to a period of general slope instability in this area, as proven in other localities (e.g., Holm et al., 2004). Mass wasting events were also certainly predisposed by long-lasting slope movements, as their failure zones are linked to some of the DGSDs scarps observed on both sides of the valley (Figure 1c; Pigazzi et al., 2022).

Clues on the climate of Piuro come from the historical documentation (Scaramellini et al., 1995). Its mansions were renowned for the beauty of their orchards and gardens, where fruits as peaches, lemons and citruses were cultivated at the end of the 15th century (Gianasso et al., 2000). Because these plants are particularly susceptible to frost in late winter–spring and during fruiting (e.g., Conesa et al., 2015; Liu & Sherif, 2019), a mild climate might be suggested. Moreover, many testimonies talk about a week of intense and incessant rainfall in the days just before the landslide.

3D numerical modelling of the PL, performed by a coupled hydro-mechanical analysis, shows how an intense water supply, estimated in a cumulated rainfall of 345 mm within 5 days, could have led to the slope failure (Morcioni et al., 2023). This rainfall amount has a 200-year return period, and it is envisaged for this kind of event, comparable to the episode that brought to severe flood emergency in nearby regions (e.g., Alexander, 1988; Botta, 1987; Morcioni et al., 2023).

In light of these observations, the 1618 landslide might have occurred during one of the LIA's warm periods in this sector of the Alps, triggered by intense precipitations that may also have been accompanied by a phase of progressive permafrost melting at gradually increasing elevations. A comparable setting is likely also for the MRL, which predates the LIA, but because its pre-Roman age is not yet tightly constrained, the relationship with the post-glacial climate cycles remains an open question.

Concerning the seismicity of this area, the Engadine Line was still active, as evidenced by recent historical earthquakes in the Engadine/Bregaglia region (Rovida et al., 2020, 2022). Some findings suggest that the Engadine–Gruf tectonic system may have been also active during the Pleistocene, contributing to the development of several DGSDs in the Bregaglia Valley (Tibaldi & Pasquarè, 2008). In other sectors of the Alps, tectonic activity has been proven to be one of the principal triggering factors for large landslides (e.g., Viganò et al., 2021). Although seismicity cannot be considered a triggering factor for the 1618 landslide (Baratta, 1901), it cannot be excluded as a triggering factor for the MRL, comparably to other events in the region, especially in prehistoric times.

6 | CONCLUSIONS

The Piuro case study shows how geological, geomorphological, climatic and human evolutions are intimately interconnected in an active environment such as an Alpine valley. The increments of historical landscape evolution were unravelled, thanks to the occurrence of two large-scale landslide events whose deposits widely reshaped the valley floor, providing two key geomorphological turning points.

Stratigraphic analyses and the study of the spatial and temporal relations between the sedimentary bodies and the corresponding landforms permitted to interpret their relative depositional chronology. Step-by-step backward subtraction of the lithosomes and landforms from the present-day topography permitted to interpret the morphology of the valley floor and lower slopes before and after the catastrophic turning points and during the interlude between them. Based on these data, two paleo-DTMs were computed, corresponding to the landscapes predating and immediately post-dating the 1618 event. Computing the difference between the two paleo-DTMs, an estimate of the volume of the landslide of about 7 Mm^3 was obtained, in keeping with the independent estimates based on the volume of the slide-scar. This comparison strengthens the reconstruction of the landslide size and provides an indirect validation of the paleo-DTMs.

The buried stratigraphy shows that after de-glaciation, the valley at Piuro was occupied by the Mera trunk river and by the oldest lobes of the lateral debris-flow fans that were already larger on the northern than on the southern side. On both the valley slopes, DGSDs mobilized the bed-rock, slowly displacing also the glacial deposits and landforms, and progressively intensified the degradation processes, predisposing slopes to landslide phenomena.

The MRL occurred at least 1.5 ka before the 1618 Piuro catastrophe; it barred and diverted the Mera trunk river and built humps tens of metres high above the centre of the valley floor.

During the interlude between the two landslides, cyclical avulsions activated different lateral debris-flow fan lobes that prograded towards the valley axis, burying the MRL deposits but the most elevated humps. Geomorphological stabilization occurred on a decadal to secular scale on the abandoned fan lobes, on the uppermost trunk river terraces and on the top of the relic MRL humps. These were the sites for human settlements predating the modern Piuro. Since the Middle Ages, the growth of the ancient village was driven by commerce, soapstone manufactures and flourishing agriculture under mild climate. It led to the extensive occupation of the valley, regardless of slope instability processes, but taking care of sheltering mostly from the decadal occurrence of trunk river and debris-flow fans floods. This setting is represented by the pre-1618 paleo-DTM that compares positively to the most reliable landscape elements recurring in the historical paintings.

The 1618 PL buried the valley floor, fossilizing most of the MRL humps, long segments of the Mera lower terrace and large parts of the debris-flow fan lobes, leading to destruction of most of the Piuro settlements. It also barred the Mera River to the East, causing a short-lived damming effect. The remnant buildings and the wiped out but not buried settlements help to delimit the outer reaches of the landslide body. Some of them will be destroyed or buried by posterior events, related to debris flows and floods on the lateral fans.

Since 1618, the Mera River started to carve its new course eroding the landslide deposits, while new debris-flow fan lobes prograded from both the valley sides during several decadal increments, leading to substantial reworking and burial of the landslide body, whose original areal extent and volume were largely masked. New settlements occupied almost immediately the Piuro area, again under the concern of protection from floods that is still going on by regimentation of the streams.

The chronology of landscape evolution increments, the paleo-DTMs and the qualitative maps resulting from this study contribute to shape the setting for archaeological research on the area. The reconstruction documents in detail the evolution of an Alpine valley floor after de-glaciation and during the climate cycles predating and postdating the LIA. The climate control on the occurrence of the 1618 landslide by long-lasting rainfalls likely coupled with permafrost thawing during a LIA warm and humid interlude is strongly constrained.

On the other hand, the DGSDs controlled the sites where the slope failures occurred on both the northern and southern slopes from which detached respectively the former MRL and the subsequent PL. Seismic trigger may be safely excluded for the 1618 event, differently from the former MRL for which no sufficient constraints are available.

The reconstruction shows the temporal scale of recurrence of the different hazardous processes. In the Piuro setting, large-scale landslides were occasionally separated by a millennial lag, while the largest debris-flow events recur cyclically on a decadal scale. Stabilization of morphological surfaces, on debris-flow fan lobes, alluvial terraces and base of slope settings occurs on a secular scale, controlling the location and duration of settlements. The pluri-disciplinary method set-up for this study looks to be promising for application to different mountain and climate settings and to different aims. The identification of morphological markers in the geological evolution of an area allows to determine its geological activity over a specific temporal range. The implementation of 3D DTMs depicting different phases of this evolution permits to make quantitative analyses of landscape changes over time, the more precise the more chronological and geometrical constraints have been considered. Combining them with historical and climate datasets would make it possible to analyse the correlations between climate and landscape. The general trend towards warmer conditions recorded in high mountain regions around the world may significantly influence the frequency of slope failures, as already suggested by several studies (e.g., Huggel et al., 2012). Fluctuation of the limits of peri-glacial environments may lead to increasing instability of the higher portions of mountain environments, as seems to be conceivable for the warm LIA interludes in this sector of the Alps. Knowledge of the past geological evolution of this environment should help to steer risk reduction measures in the near future.

AUTHOR CONTRIBUTIONS

Conceptualization: Enrico Pigazzi, Riccardo Bersezio and Tiziana Apuani. *Funding acquisition*: Tiziana Apuani. *Methodology*: Enrico Pigazzi, Riccardo Bersezio and Tiziana Apuani. *Investigation*: Enrico Pigazzi and Riccardo Bersezio. *Resources*: Tiziana Apuani. *Software*: Enrico Pigazzi and Federica Marotta. *Supervision*: Riccardo Bersezio and Tiziana Apuani. *Initial draft*: Enrico Pigazzi and Riccardo Bersezio. *Reviewing and editing*: Riccardo Bersezio, Tiziana Apuani and Federica Marotta.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Enrico Pigazzi, upon reasonable request.

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