Journal of Maps

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

Disentangling the stratigraphic architecture of the Rivoli-Avigliana end moraine system (Western Alps, NW Italy)

Gianfranco Fioraso, Giovanni Monegato, Gianni Balestro, Irka Hajdas & Paolo Baggio

JOURNAL OF MAPS
https://doi.org/10.1080/17445647.2021.1942252

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

SCIENCE

Disentangling the stratigraphic architecture of the Rivoli-Avigliana end moraine system (Western Alps, NW Italy)

Gianfranco Fioraso [a], Giovanni Monegato [b], Gianni Balestro [c], Irka Hajdas [d] and Paolo Baggio[e]

[a]Institute of Geoscience and Earth Resources – National Research Council, Turin, Italy; [b]Institute of Geoscience and Earth Resources – National Research Council, Padova, Italy; [c]Department of Earth Sciences, University of Turin, Turin, Italy; [d]Laboratory of Ion Beam Physics, ETH Zurich, Zurich, Switzerland; [e]SGB Studio Geologico Baggio, Turin, Italy

ABSTRACT
The Rivoli-Avigliana end moraine system (Italian Western Alps) hosts an important stratigraphic archive of Pleistocene glaciations. A new geological map provides a 3D architecture of the system that reveals a complex architecture of glacial, alluvial and lacustrine units. Six glacial units were recognized. During the deposition of the four older glacial units (Early-Middle Pleistocene) the morphology of the valley outlet had a different drainage pattern from the present, with the presence of large lakes. From the penultimate glaciation to the Last Glacial Maximum (LGM) the piedmont lobe was confined within the valley, never extending towards the alluvial Po Plain. The LGM is characterized by two glacial advances and four distinct recessional phases during the Lateglacial. The presence of a bedrock inselberg affected the flow of the glacier front, which should have had weak erosive strength as shown by the preservation of lacustrine deposits below the glacial units.

ARTICLE HISTORY
Received 2 February 2021
Revised 2 June 2021
Accepted 4 June 2021

KEYWORDS
Italian Western Alps; Rivoli-Avigliana end moraine system; glacigenic deposit; ^{14}C, geomorphology

1. Introduction

The glacial end moraine systems, also called morainic amphitheatres, are characteristic glacial landforms of Alpine valley outlets. They are the result of multiple advances of glacial piedmont lobes, which spread out from the European Alps during the Pleistocene cold periods. Their stratigraphic reconstruction promoted, since the late nineteenth century (Gastaldi, 1872), the concept of glaciations and the development of the fourfold chronostratigraphic subdivision of Penck and Brückner (1909). The stratigraphic architecture of an end moraine system is strongly influenced by the configuration and dynamics of the glacial piedmont lobe and then of the terminal moraines. The size of the valley glacier, which can be considerably different from one cold phase to another, is the leading factor for the configuration of terminal moraines. The shape of the valley outlet, the inheritance of the river thalweg, and the presence of irregular bedrock morphologies also contribute to shape the glacier piedmont lobe. Another possible driver, on long time scales, is active tectonics that can change the topography and change river paths (Carraro & Petrucci, 1977).

The Rivoli-Avigliana end moraine system, located at the outlet of the Susa Valley (Dora Riparia basin) in the European Western Alps, is the westernmost of the end moraine systems that reach the alluvial Po Plain (Figure 1). Unlike other end moraine systems located on the southern side of the Alps (e.g. Ivrea, Garda, Tagliamento), the Rivoli-Avigliana amphitheatre shows an unusual ‘bullet shape’ instead of the ‘classic’ concentric arcuate pattern. Since the mid-nineteenth century, this end moraine system has been the subject of numerous stratigraphic and morphological studies (Capeder, 1904; Martins & Gastaldi, 1850; Prever, 1907; Sacco, 1887). Subsequently, the climato-stratigraphic model of Penck and Brückner (1909) was applied to the Rivoli-Avigliana amphitheatre by Sacco (1921), Mattirolo et al. (1913), Mattirolo et al. (1925), Bortolami et al. (1969) and Petrucci (1970). A complete cartographic review was recently carried out by Balestro et al. (2009a) in the frame of the CARG Project (National Geological Cartography), mainly based on morphostratigraphic and pedostratigraphic criteria. Unfortunately, despite the extensive studies conducted in the past, in the absence of radiometric and subsurface data, the age and the stratigraphic relationships of the moraines have often remained uncertain and ambiguous.

Thanks to the results of a recent subsoil exploration campaign and new radiometric dating, in this paper we present a new stratigraphic architecture and a more accurate chronostratigraphy of the Rivoli-Avigliana morainic amphitheatre. Results reported in Main Map led to reconstruct the different phases of glacial advances that contributed to form the morainic amphitheatre as a whole, while the explanatory cross-

CONTACT Gianfranco Fioraso gianfranco.fioraso@cnr.it
Supplemental data for this article can be accessed here https://doi.org/10.1080/17445647.2021.1942252.

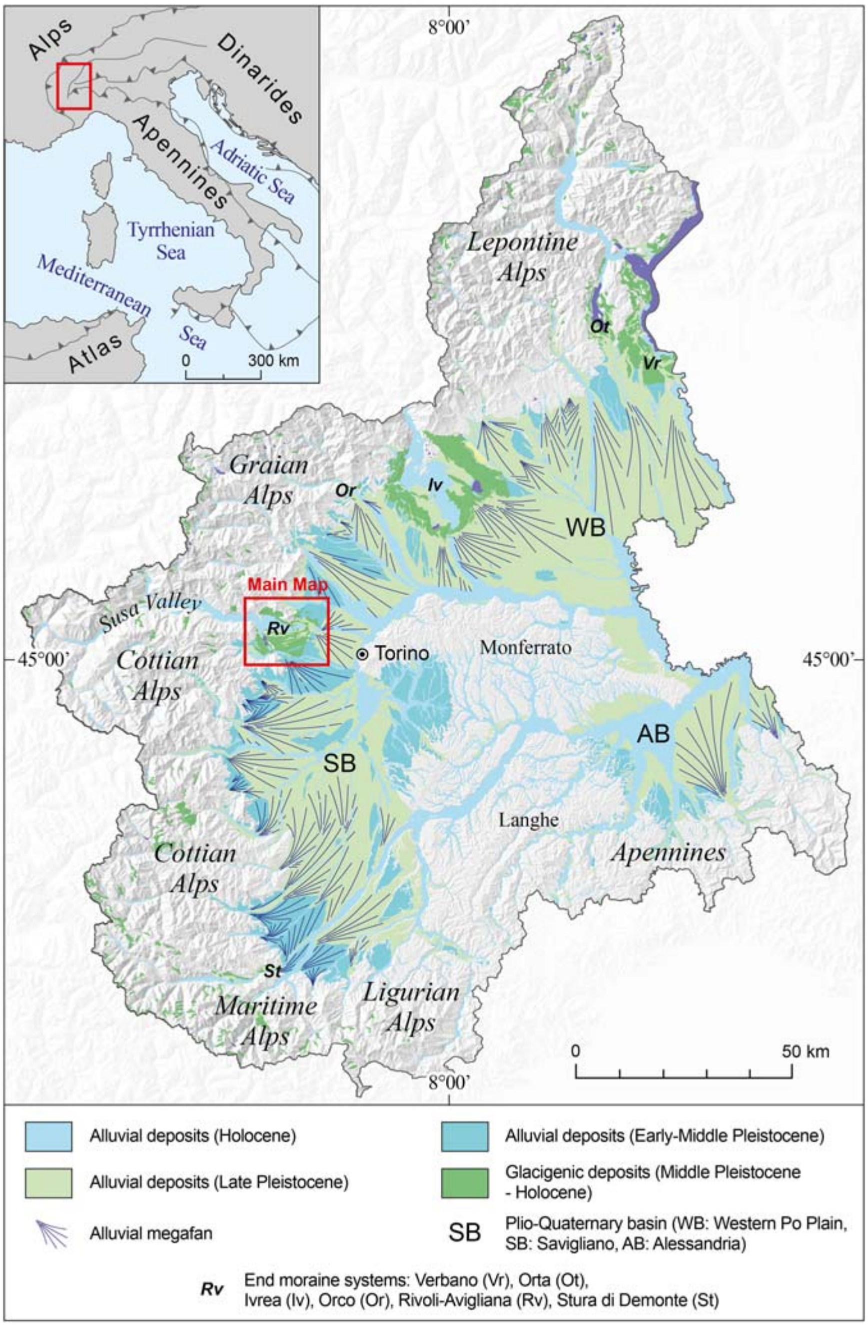

Figure 1. Geomorphological scheme of the Western Po Plain (modified from Piana et al., 2017a).

sections illustrate the intricate relationships between the different glacial and interglacial units.

2. Methods

The Main Map, designed to be at a scale of 1:25,000, encompasses an area of 291 km^2 between the Graian and Cottian Alps, at the mouth of the Susa Valley in the Western Po Plain (Figure 1). Detailed geological data and geomorphological features were collected by original mapping performed at a scale of 1:10,000. Field work was integrated with stereoscopic photo interpretation of multi-temporal aerial images.

In addition to bedrock geology and glacial, glaciofluvial, alluvial and slope deposits, some geomorphological features such as moraine ridges, erosional scarps, traces of abandoned river channels are shown in the Main Map. Particular attention was paid to the mapping of erratic boulders, often the only elements capable of attesting the outermost glacier terminal position in the lowland area.

Although exposures are rare, to define the end moraine system architecture and the relationships with the pre-glacial successions (illustrated in 6 geological cross-sections at a 1:5 h/v scale 1:25,000/1:5,000), 253 logs of boreholes (177) and water wells (76) up to 270 m deep, were collected from the geotechnical database of the Regional Agency for the Protection of the Environment (ARPA Piemonte), from the CARG Project and from other technical reports and indicated in the Main Map.

Table 1. ^{14}C data in the Rivoli-Avigliana end moraine system (previous Authors).

Code	Locality	Depth (m)	Material	Age (y BP)	Cal. age 95% of probability (y BP)	Reference
C1	LTL12084A	outcrop	charcoal	>45,000	>45,000	Ivy-Ochs et al. (2018)
C2	Villar Dora	3	wood fragment of pine	10,000 ± 75	11,805–11,253	Charrier and Peretti, (1973, 1975)
C3	Novaretto	4	peat layer	7,780 ± 100	8980–8385	Charrier and Peretti (1975)
C4	Lago Piccolo	1.75	gyttja	1,565 ± 43	1532–1364	Larocque and Finsinger (2008) Finsinger and Tinner (2006)
C4-5	Lago Piccolo	9.09	gyttja	14,930 ± 80	18,619–18,049	Larocque and Finsinger (2008) Finsinger and Tinner (2006)

Stratigraphic analysis of recent core samples (1020 m total core length) obtained from 20 drillings made it possible to collect some samples of organic matter for radiocarbon dating, which allowed for the definition of the chronostratigraphy of the Last Glacial Maximum (LGM) moraines and the withdrawal phases of the glacial front.

To better understand the dynamics of the Dora Riparia glacier in the frame of the Northern Cottian Alps, the scheme of the ice flow pattern has been inserted in the Main Map.

Field data are represented on a vector topographic map partially derived from the 'Carta Tecnica Regionale Numerica' at a scale of 1:10,000 of the Piemonte Region (Coordinate System WGS 1984 UTM, Zone 32N); contours at 20 m intervals were derived by the LiDAR DTM with 5 m resolution of the Piemonte Region (DTM LiDAR 2009–2011 Piemonte ICE).

Radiocarbon ages (Tables 1 and 2) were calibrated using the INTCAL20 calibration curve (Reimer et al., 2020). The $\delta^{13}C$ values of samples analysed at ETH were measured on graphite.

3. Morphological and geological setting

The Rivoli-Avigliana end moraine system extends at the mouth of the Susa Valley over an area of about 180 km^2. It is bordered by the Casternone-Ceronda and Sangone rivers to the north and south, respectively, and by an extensive outwash apron to the east (cf. Main Map).

The Dora Riparia drainage basin covers an area of 1267 km^2, with mountain peaks that sometimes exceed 3500 m a.s.l. (e.g. Punta Roncia, 3612 m; Mt. Rocciamelone, 3537 m; Pierre Menue, 3506 m) and a minimum elevation of 315 m at the Alpignano gorge. Mean elevation of the catchment is 1709 m. The trunk valley extends west–east for about 83 km. After exiting the Alpignano gorge, the river cuts the outwash plain to join the Po River in the city of Turin, at 210 m a.s.l.

Along the drainage divide, some prominent morphological saddles, mainly induced by glacial erosion, are present: from north to south the Moncenisio (2081 m), Piccolo Moncenisio (2183 m), Thures (2194 m), Scala (1762 m), Monginevro (1850 m), Bousson (2154 m), Chabaud (2213 m) and Sestriere (2035 m) passes (cf. scheme of the ice flow pattern in the Main Map). During Pleistocene glacial spreading out, across these saddles glaciers spilled over the divide to and from the adjacent glacier systems (namely the Arc, Durance and Chisone glaciers), with implications for drainage patterns (Cossart et al., 2012; Fioraso & Mosca, 2020; Polino et al., 2002) and possibly on glacier front dynamics.

The bedrock of the Dora Riparia catchment is made up of continental and oceanic nappe systems, which belongs to the Pennidic domain (Piana et al., 2017a, b), and, in the Main Map, includes:

- the Lower Susa-Lanzo valleys Unit derived from the Liguria-Piemonte ocean, and consisting of mantle rocks (Lanzo Ultramafic Complex), Jurassic meta-ophiolites and Cretaceous metasediments;
- the Dora Maira Massif derived from the Palaeo-European continental margin, and consisting of Late Carboniferous metasediments, Early Permian meta-intrusive bodies and minor slices of the Mesozoic carbonate cover (Balestro et al., 2009b).

Table 2. ^{14}C data in the Rivoli-Avigliana end moraine system (present work).

Code	Lab. Sample	Unit – Lithofacies	Depth (m)	Material	^{14}C (y BP)	±1σ	Cal. Age 95% prob. (y BP)	F14C	±1σ	δC13‰	±1σ
C6	ETH-69826	F3 – laminated mud and fine sand	8.70–8.80	wood	12,009	26	14,023–13,797	0.2243	0.0007	−26.2	1
C7	ETH-69827	F3 – laminated mud	6.90–7.00	macrofossils	10,122	24	11,867–11,412	0.2836	0.0009	−26.9	1
C8	ETH-69828	F3 – peat	7.20	macrofossils	10,034	25	11,730–11,350	0.2867	0.0009	−23.4	1
C9	ETH-69829	F3 – sandy mud	17.80	macrofossils	13,880	28	17,016–16,701	0.1777	0.0006	−25.2	1
C10	ETH-69830	L1 – laminated mud	18.50	macrofossils	>50,700		–	<0.0018		−28.4	1
C11	ETH-69831	L1 – laminated sandy mud with gyttja	25.80	macrofossils	>48,300		–	<0.0025		−27.9	1
C12	ETH-69832	A2f – mud	8.50	charcoal	>48,400		–	<0.0024		−28.3	1

The lower reach of the valley includes Pliocene coastal to continental deposits (Villafranchian *Auct.*; Martinetto et al., 2007) and Early Pleistocene alluvial sediments (Balestro et al., 2009a).

4. Stratigraphic units and map representation

In the past, Bortolami et al. (1969) and Petrucci (1970) adopted a combined morpho-lithostratigraphical approach for the stratigraphic subdivision of the Rivoli-Avigliana amphitheatre. However, as evidenced by Räsänen et al. (2009) and Hughes (2010), some difficulties arised in the use of this approach in the glacigenic terrains, (i) due to the complexity and small-scale lithologic variation in this deposits, and (ii) because unconformities are very common in glacigenic deposits due to the erosional dynamic and depositional processes combined with the repeated pattern of glacial cycles. Other factors make morpho-lithostratigraphy unreasonable in the Rivoli-Avigliana area, such as the presence of glacial units not morphologically expressed at the surface because buried or eroded by more recent sediments, and the presence of many buried unconformities identified only by subsurface investigations. For these reasons, the stratigraphic subdivision of the Rivoli-Avigliana amphitheatre was accomplished by means of Unconformity-Bounded Stratigraphic Units (synthems) (Chang, 1975; Salvador, 1994), analogous to allostratigraphic units (Dahms, 2002; NACSN, 1983; Passchier et al., 2009), and adopted in the Italian Geological Map Project (Germani et al., 2003) for mapping Quaternary alluvial and glacial successions (Balestro et al., 2009a; Bini et al., 2004a).

The bounding surfaces were identified in cores or in outcrops on the basis of the occurrence of paleosols, sharp changes in sedimentology, including provenance, and identifiable erosional surfaces. The boundaries were then traced using available information in order to set up reliable relationships among the different units. In order to establish a relative chronology of the moraines of different glaciations, in addition to their positions and morphological evidence, their sedimentary sequence, and description of soil profiles provide useful data, although in some cases soils have been deeply affected by erosion and re-depositional processes.

In the Main Map, the colluvial deposits were only represented in the bedrock sectors, whereas in the end moraine system these were not considered in order to give a better map representation of the stratigraphic architecture. In the same stratigraphic unit (synthem or sub-synthem), different lithofacies were mapped by the use of specific graphic patterns and label subscripts. The relationships among the stratigraphic units are detailed through six geological cross-sections. In the Main Map legend, five pre-LGM glacigenic units were distinguished, while four pre-glacial (non-glacigenic) units were mapped. LGM and Lateglacial glacigenic units were split into five sub-units, while three Holocene alluvial and lacustrine units were distinguished.

5. Architecture of the Rivoli-Avigliana end moraine system

The most characteristic feature of the Rivoli-Avigliana amphitheatre is the marked geomorphic asymmetry of the moraine systems, due to the physical constraints imposed on the ice flow by the irregular configuration of the bedrock at the mouth of the Susa Valley.

East of the prominent rocky ridge of Torre del Colle, the northern sector of the amphitheatre appears confined close to the southern steep slope of the Mt. Curt–Mt. Musiné mountain ridge (Figures 2(a) and 3(a)). A cluster of well-preserved lateral moraines is found near Rubiana, where the glacier repeatedly dammed the Messa Creek during glacial expansions.

To the east and south, a complex of densely spaced moraines covers the area between the Casternone-Ceronda and the Sangone rivers, gradually fading into the outer glaciofluvial apron. The continuity of the moraines is interrupted by the gorge of the Dora Riparia River, up to 50 m deep, that cross-cuts the entire glacial succession, and by some other watergaps created by the meltwater flowing out the glacier front.

Southwards, the NNW-SSE-trending inselberg of the Mt. Moncuni (641 m a.s.l.) caused the glacier to split into two distinct lobes (Figure 2(a,b)), of which the right one went up the lower Sangone Valley, forcing the stream to flow across the rocky saddle between the Mt. Moncuni and the Mt. Pietraborga (Figure 3(b)).

5.1. Pre-glacial units

The Rivoli-Avigliana end moraine system is the result of the spread on the Western Po Plain of a piedmont lobe of the Dora Riparia glacier during Pleistocene glaciations. Beyond the outermost moraines, extensive sandur fans and proglacial outwash deposits are mapped. However, the rare exposures and the subsurface geology reveals that the glacier foreland is characterized by a succession of crudely bedded coarse pebbly gravels, here referred to the Pianezza and Alpignano synthems, early to middle Pleistocene in age, that are separated by a thick paleosoil (Figure 4(a)). With an overall thickness of 40–50 m, these units crop out along the Dora Riparia gorge east of Alpignano (section *F–F′* in the Main Map), buried by a veneer of glacial till. At the base of the southwestern slope of the peridotite reliefs of the Mt. Curt–Mt. Musiné mountain ridge, glacial till masks a thick succession of strongly cemented, redden, coarse-grained

Figure 2. Panoramic views of the Rivoli-Avigliana end moraine system. Triangles indicate the main moraine ridges. (a) Photo taken from Mt. Pietraborga (7°25′18″ E, 45°01′18″ N), looking North. The Sangone River is visible in foreground. Black triangles: Truc Bandiera synthem. Red triangles: Truc Monsagnasco synthem. Yellow triangles: Cresta Grande synthem. White triangles: Truc Morté sub-synthem. T: Trana peat bog. (b) Photo taken from Cima Castiglione (7°20′41″ E, 45°05′10″ N), looking East. In the middleground the Avigliana lakes (Lago Grande and Lago Piccolo) are visible. Black triangles: Caselette sub-synthem. Red triangles: Truc Morté sub-synthem. Yellow triangles: S. Antonio di Ranverso sub-synthem. White triangles: Avigliana sub-synthem. M: Mareschi swamp. T: Trana peatbog. (c) Photo taken from Mt. Musiné (7°27′17″ E, 45°06′49″ N), looking South-East. The Dora Riparia alluvial plain is visible in foreground. Yellow triangles: Cresta Grande synthem. White triangles: Truc della Pra sub-synthem.

alluvial and debris flow deposits ascribed to the Almese Unit and Gelasian to Calabrian in age (Balestro et al., 2009a) (Figure 4(b)).

A sharp regional basal unconformity separates the previous units by a thick succession referred to the La Cassa Unit ('Villafranchian' *Auct*.; Carraro, 1996) (Balestro et al., 2009a), characterizing the piedmont plain of the Western Alps and easily identifiable in the cores. This unit, outcropping along the thalweg of the Casternone-Ceronda River, is made up of gravelly and silty-sandy floodplain deposits with a characteristic ochre colour, and preserves lignite coal beds and abundant palaeobotanical remains attributed to the Piacenzian by Martinetto et al. (2007).

5.2. Pre LGM glacigenic units

The oldest preserved glacigenic unit of the Dora Riparia glacial landsystem is the Sangano synthem (B5), which crops out in a few places in the southern flank of the end moraine system (between Trana and Bruino), where flat terraces with a few scattered erratics are the only remnants, whereas moraines have been completely dismantled by fluvial erosion. Weathered glacial till with an average thickness of 15 m was also found in some cores close to Rivalta. The diamicton of this unit is always very weathered, with 5YR 2 to 3 m thick soil, and rests unconformably on the Alpignano Unit (cross-sections *D–D′* and *E–E′* in the

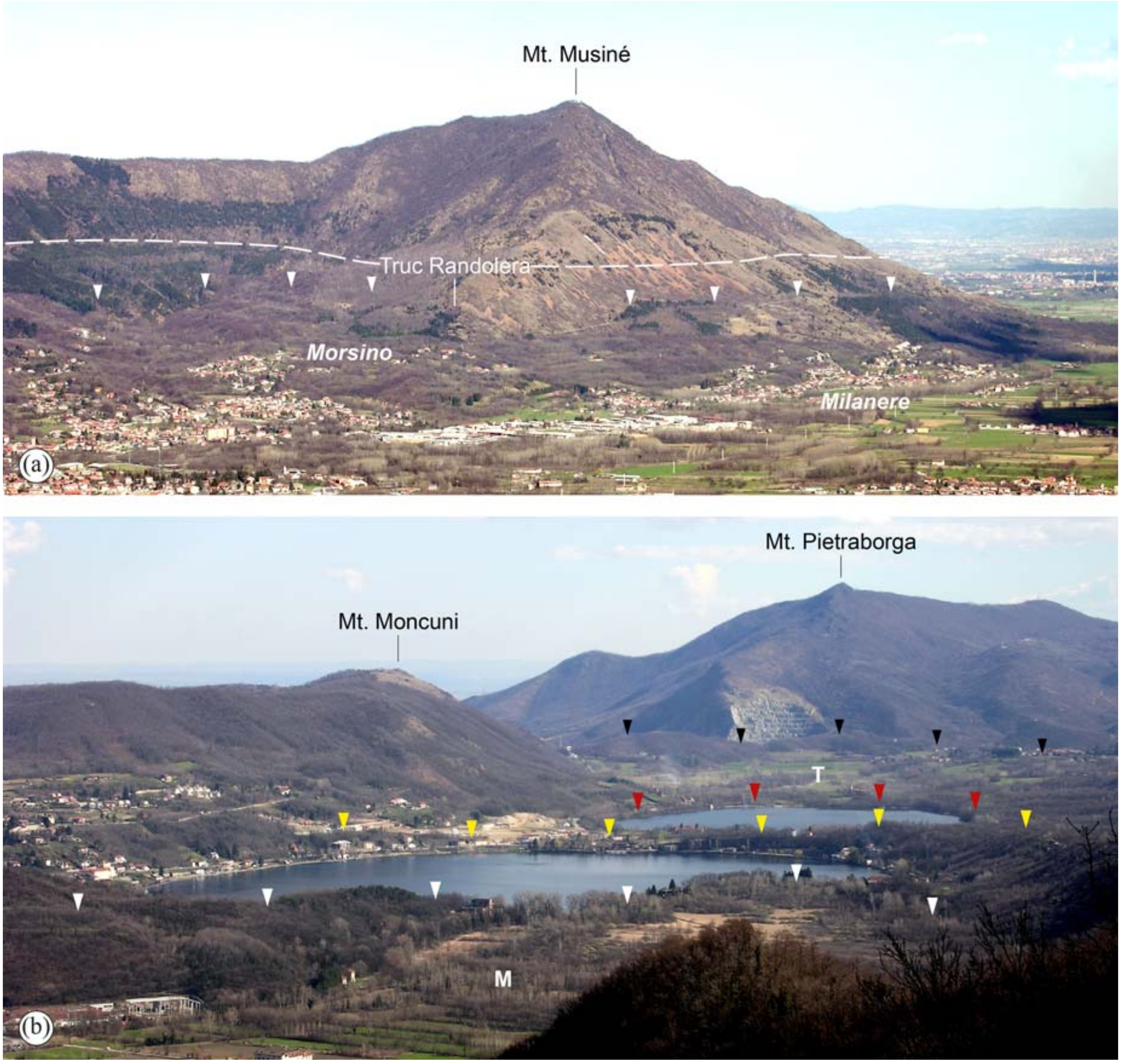

Figure 3. (a) The mouth of the Susa Valley dominated by the southern slope of the Mt. Musiné. On the right, in the background, the Turin Hill is visible. White triangles: maximum limit of the glacier during the LGM (Caselette sub-synthem). Dotted line: maximum elevation of the glacial deposits preserved along the peridotitic mountainside. Photo taken from the Sacra di S. Michele (7° 20′34″ E, 45°05′53″ N). (b) The Avigliana lakes (Lago Grande, in foreground, and Lago Piccolo) are visible. Black triangles: Truc Morté sub-synthem. Red triangles: Truc della Pra sub-synthem. Yellow triangles: S. Antonio di Ranverso sub-synthem. White triangles: Avigliana sub-synthem. M: Mareschi swamp. T: Trana peat bog. Photo taken from the eastern slope of Cima Castiglione (7° 21′32″ E, 45°05′05″ N), looking South-East.

Main Map). In other sectors of the amphitheatre, the lack of morphological evidence for the Sangano synthem can be explained by the overprinting of subsequent glacier re-advances.

The outermost moraines of the Rivoli-Avigliana amphitheatre, referred to as the Truc Bandiera synthem (B4), are preserved in its southern sector, just north of the Sangone River (Figures 2(a) and 4 (c)). They appear as a couple of large and imposing moraines with smooth crests, characterized by 5YR 2–3 m thick paleosols and with patchy loess cover up to few metres thick. Another cluster of rounded moraines is preserved on the northeastern flank of Mt. Moncuni. Some smoothed, more discontinuous moraines are also visible in the eastern and northern sectors of the amphitheatre close to Grugliasco and San Gillio, respectively. Correlative glaciofluvial deposits are preserved in high terraces between San Gillio and Druento. As clearly evidenced by subsurface data, the Truc Bandiera synthem rests unconformably on the Pianezza and Alpignano units (cross-sections *D–D′* and *E–E′* in the Main Map).

Like the previous one, the Truc Monsagnasco synthem (B3) is morphologically well preserved in the southern sector of the amphitheatre (Figure 2 (a)), with imposing although discontinuous moraine, whereas in the eastern and northeastern area it is characterized by large, flat moraines. The till and the patchy loess cover are weathered, with a 7.5–5 YR 1–3 m thick soil. This unit rests unconformably on the Alpignano synthem (cross-section *F–F′* in the Main Map). Very large serpentinite and metabasite erratic

Figure 4. (a) Erosional contact between the strong weathered, massive gravelly deposit of the Pianezza synthem (PN) and the well cemented gravelly deposit of the Alpignano synthem (AP) (man for scale). Photo taken along the left bank of the Dora Riparia River, 1.2 km SE of Pianezza (7°33′33″ E, 45°05′27″ N). (b) Chaotic, rubified debris flow deposit of the Almese unit (AM) topped by till of the Caselette synthem (A5) outcropping along the Rio Morsino (North-Western slope of the Mt. Musiné; 7°26′03″ E, 45° 07′15″ N). (c) Impressive stratigraphic section (700 m long and up to 60 m high) of the Truc Bandiera synthem (B4), made up of prevailing lodgement and melt-out till, visible along the left bank of the Sangone River, 1 km NNW of Sangano (7°26′42″ E, 45° 02′16″ N). (d) Sharp contact between lodgement (l) and melt-out (m) till of the Truc Morté sub-synthem (A4) (left bank of the Sangone River, 1 km WSW of Trana; 7°24′26″ E, 45°01′59″ N). (e) The 'Masso Gastaldi', in the centre of Pianezza (7°33′01″ E, 45°05′56″ N), is the largest erratic of the Rivoli-Avigliana amphitheatre (38 m long, 25 m wide and 14 m high). (f) The 'Pera Majana', a serpentinite boulder 32 m long, 23 m wide and 6 m high visible in the centre of a large outwash channel close to Villarbasse (7°28′43″ E, 45°02′35″ N).

boulders are included in this unit: the 'Masso Gastaldi', located in the centre of Pianezza (Figure 4(e)), is the largest erratic in the amphitheatre (38 m long, 25 m wide and 14 m high), whereas the 'Pera Majana' is a serpentinite boulder, 32 m long, 23 m wide and 6 m high, abandoned in the centre of a large outwash channel close to Villarbasse (Figure 4(f)).

The Truc Carlevé synthem (B2) is continuous along the end moraine system, including the Avigliana lakes lobe, close to Giaveno. The unit is characterized by discontinuous flat moraines, in many cases showing a sinuous or multilobate pattern and anomalous cross-directions with respect to other moraine clusters. In some places (i.e. between Reano and Rivoli) individual crests are superimposed by the youngest moraines of the Cresta Grande synthem. Thickness of Truc Carlevé synthem reaches 150–180 m at Truc Carlevé (cross-section *D*–*D*′ in the Main Map). The deposits are weathered with soil colour reaching 5YR. The correlative glaciofluvial fan is well preserved only in the southeastern flank of the glacial system. Subsurface investigations reveal that a lacustrine unit (L3) lies between Truc Carlevé and Truc Monsagnasco synthems, suggesting a damming of the valley outlet (cf. cross-section *B*–*B*′ in the Main Map).

The Cresta Grande synthem (B1) includes the highest morainic ridges of the amphitheatre (Figure 2(a, c)), and it is continuous throughout the valley outlet, including the southern slope of the Rocca Sella–Mt. Arpon and Mt. Curt–Mt. Musiné mountain ridges. Two major moraines with subsidiary ridges are well preserved south of the Dora Riparia River and near Rubiana, while to the northeast moraines show a low and flat profile. The diamicton of this unit shows a 10–7.5YR 1–2 m thick soil. The correlative glaciofluvial deposits are preserved in the eastern sector (between Pianezza and Rivoli), forming large terraces. The Cresta Grande synthem lays on a thick lacustrine succession (L2; cross-sections *B–B′*, *D–D′*, *E–E′* in the Main Map), intercepted by some boreholes. This marks a phase of damming of the valley outlet, likely related to the frontal moraines. Other lacustrine sediments, due to local moraine damming, are visible at the mouth of the Messa valley, near Rubiana: here, radiocarbon dates showed ages beyond the method indicating pre-LGM deposition (Ivy-Ochs et al., 2018) (C1, Table 1). Another lacustrine succession (L1) marks the transition from the Cresta Grande synthem to the LGM and Lateglacial glacigenic units. With an estimated thickness of at least 40 m, L1 extends south of the Dora Riparia River, between Avigliana, Buttigliera Alta and Rosta (cross-sections *B–B′* and *D–D′* in the Main Map). Also, in this case, radiocarbon dates performed on two sediment cores, C10 and C11 (Table 2), showed ages beyond the method (>50,700 and >48,300 cal. years BP, respectively) also indicating a pre-LGM deposition.

5.3. LGM and Lateglacial units

The LGM succession of the Rivoli-Avigliana morainic amphitheatre was split into five sub-synthems related to maximum advances (Caselette and Truc Morté sub-synthems; Figure 2(b)) and withdrawal phases (Truc della Pra, S. Antonio di Ranverso and Avigliana sub-synthems; Figure 2(b,c)). Analysis of subsurface data confirms that the overall succession has a maximum thickness of about 100 m, although in many sectors is just a few tens of metres thick. The extent of the LGM glacier front is established by a well-developed system of continuous and sinuous moraines, some of which are closely spaced with steep crest slopes. On the other hand, ice-marginal oscillations during post-LGM deglaciation are documented by widely spaced moraine clusters, less voluminous and progressively lower than the most ancient ones due to rapid changing of the glacier volume and position. With the gradual melting of the glacier, progressively greater confinement of the ice volume is exerted by the bedrock emerging from the ice tongue surface, as evidenced by the change in moraine plan forms near the ophiolitic inselberg of Mt. Capretto, north of Lago Grande (Figure 5). LGM and Lateglacial moraines show thin (20–100 cm) soil profiles with colour ranging from 7.5YR to 2.5Y: noteworthy is the presence of fresh, unweathered limestone pebbles (Figure 4(d)). ^{10}Be cosmogenic nuclide datings from two gneissic erratic boulders sampled within the Caselette synthem along the southwestern slope of the Mt. Moncuni gave ages between 24.0 ± 1.45 and 20.9 ± 2.1 ka (Ivy-Ochs et al., 2018) (Be1 and Be2; Table 3).

During the Lateglacial phase, the Dora Riparia glacial front halted repeatedly, as evidenced by frontal moraines south of Avigliana and between Caselette and Rosta, causing the formation of some dammed lakes (i.e. Lago Piccolo and Lago Grande; Figure 3 (b)). Radiocarbon dates were obtained from a sediment core (14.9 m in length) extracted from the bottom of the Lago Piccolo di Avigliana, the youngest and oldest of which are 1445 ± 95 and 18,275 ± 325 cal. years BP, respectively (C4–C5; Table 1) (Finsinger & Tinner, 2006; Larocque & Finsinger, 2008). The glaciofluvial deposits related to the LGM and recessional phases are preserved in the terraces sequence east of the Alpignano gorge and downstream the fluvial threshold of Trana.

5.4. Post-LGM lacustrine and alluvial units

As the glacier collapsed, it left a deep depression occupied by an extensive lake blocked by Lateglacial frontal moraines. The subglacial topography as well as the palaeobathymetry (depth and longitudinal extension) of the postglacial lake are not well known. Nevertheless, near Avigliana a water well crossed a fine-grained, silty-sandy lacustrine succession (F3 unit in the Main Map) for at least 276 m depth, without intercepting the base. Some radiocarbon dating obtained from sediment cores sampled near Avigliana indicate ages of the lacustrine deposits between 17,016 and 11,350 cal. years BP (C6–C9; Table 2).

Unit F2 represents the last phase of alluvial sedimentation in the lower Susa Valley, characterized by a thin layer (5–15 m) of coarse-grained alluvial deposits and sporadic peatbogs (e.g. Villar Dora, Novaretto, Avigliana and Trana). Fossil wood remains collected near Villar Dora have been dated by Charrier and Peretti (1973, 1975) at 11,805–11,253 cal. years BP (C2, Table 1), whereas Charrier and Peretti (1975) dated peat layers sampled in some quarries near Novaretto at 8980–8385 cal. years BP (C3, Table 1).

6. Discussion and conclusions

A glacier piedmont lobe and the resultant glacial landscape is the effect of an interplay of a number of governing factors controlling glacier dynamics, such as climate, catchment characteristics (area and hypsometry), subglacial topography and geology, and geothermal heat flux (Seguinot et al., 2018). Such factors induce a different response in the individual piedmont

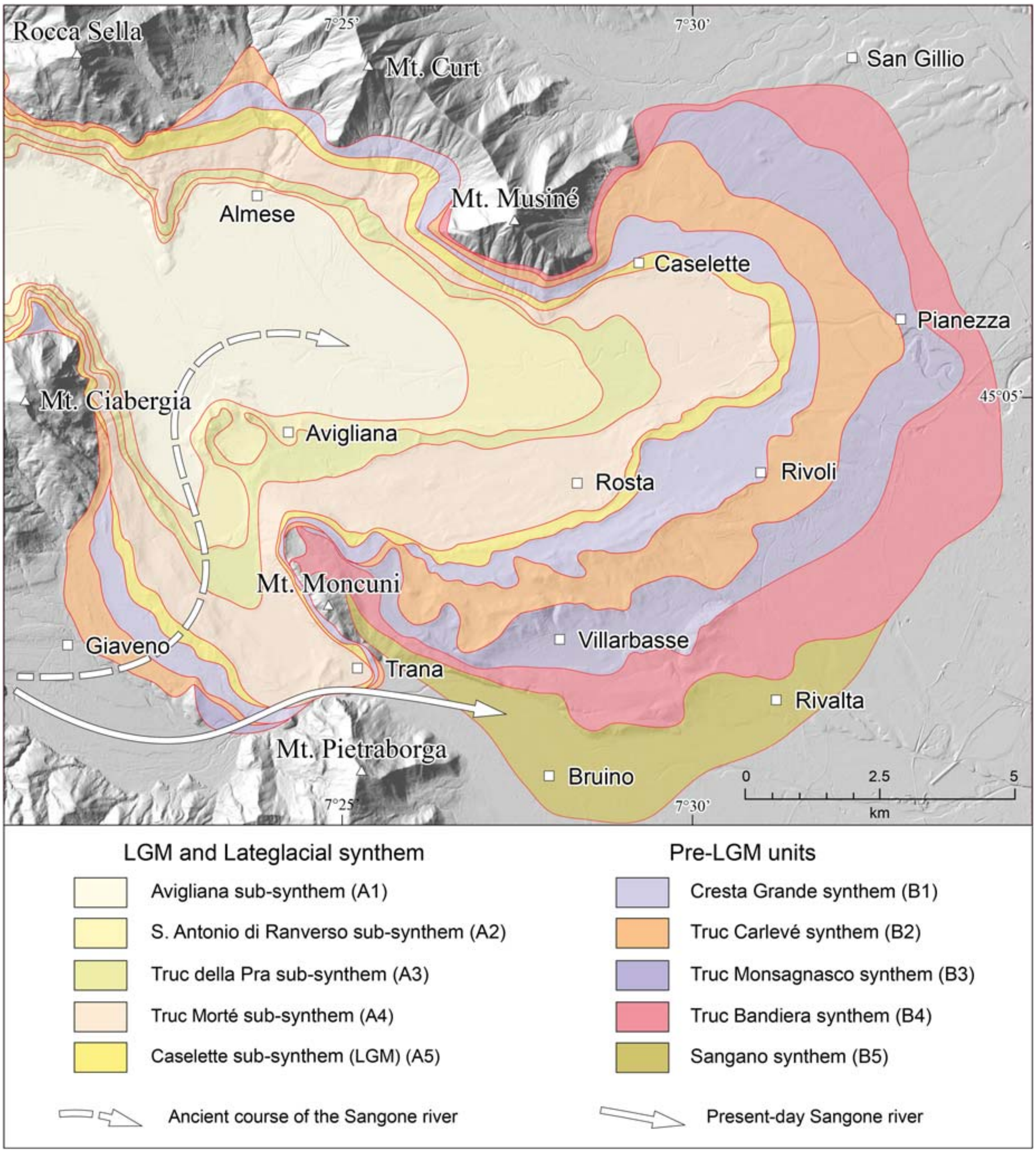

Figure 5. Scheme of the marginal position of Dora Riparia glacier during LGM and pre-LGM glaciations.

lobes and different timing of the glacier terminus position (Evans et al., 2018). The Rivoli-Avigliana end moraine system shows notable differences in its morphological setting, surface and subsurface stratigraphic architecture, number of moraines and timing of moraine deposition, if compared with the other piedmont lobes (i.e. Dora Baltea, Toce/Ticino, Adda, Adige/Garda and Tagliamento) located on the southern side of the Alps (Bini et al., 2004b; Braakhekke et al., 2020; Gianotti et al., 2015; Monegato et al., 2007, 2017). In summary, the main characteristic elements of the Rivoli-Avigliana amphitheatre can be distinguished as follows:

- a group of oldest, widely spaced glacial units (Sangano, Truc Bandiera, Truc Carlevé and Truc Monsagnasco synthems) extended in the Western Po Plain well outside the Alpine margin (Figure 5). Subsurface data indicate that moraines rest on pre-

Table 3. ^{10}Be data in the Rivoli-Avigliana end moraine system (Ivy-Ochs et al., 2018).

Code	Locality	Material	Lithology	^{10}Be (10^4 atoms/g)	Exposure age (y)
Be1	Moncuni	Erratic boulder	Gneiss	13,798 ± 811	24,030 ± 1450
Be2	Moncuni	Erratic boulder	Gneiss	2,036 ± 1.180	20,900 ± 2100
Be3	Trana	Erratic boulder	Gneiss	15,334 ± 1.163	26,800 ± 2090

glacial alluvial units (Pianezza and Alpignano synthems) without significant downcutting, suggesting that the glacier had weak erosional power at the terminus. A complete reorganization of the hydrographic network occurred since the first maximum glacial expansion documented in the area (Sangano synthem), with the Sangone River, once a right tributary of the Dora Riparia, forced to abandon the N-S trending depression beneath the present Lago Grande and Lago Piccolo and then flow south of the inselberg of the Mt. Moncuni (Figure 5). Similarly, the Casternone River has undergone a northward migration with respect to its original course as evidenced by its arcuate shape;

- a second group of regular and concentric, close-spaced moraines referred to as the Cresta Grande synthem and to the Caselette (LGM) and Truc Morté sub-synthem, constitutes the more prominent feature of the amphitheatre. Unlike the previous ones, these units rest on extensive lacustrine plateaux, confined in the southern part of the amphitheatre between Avigliana, Buttigliera and Rosta, and that have been spared from glacial erosion;
- a discontinuous, widely-spaced pattern of lateglacial recessional moraines, partially buried under the thick (more than 270 m deep) lacustrine and alluvial sequence (F3-F2 units) that fills the palaeo-depression localized along the main glacial valley. Unfortunately, neither seismic investigations nor very deep drill-holes have yet provided conclusive evidence to clarify the genesis of this palaeotopography: (i) fluvial entrenchment induced by the Messinian salinity crisis (Bini et al., 1978; Finckh, 1978) or (ii) valley over-deepening induced solely by glacial scouring (Preusser et al., 2010), as evidenced in other glaciated valleys of the Western Italian Alps, such as the Chisone and Stura di Demonte valleys (Aigotti & Ratti, 1981; Ognibeni & Venzo, 1951).

The glacial history of the Rivoli-Avigliana end moraine system prior to the LGM still remains chronologically poorly constrained. However, the comparison between previous ^{10}Be cosmogenic nuclide dating (Ivy-Ochs et al., 2018), the new radiocarbon data and subsoil investigations clearly indicates the continuous set of moraine ridges of the Caselette synthem as the LGM terminus position of the Dora Riparia glacier.

Software

The topographic map, the geological map and the related database were edited with QGIS 3.4.8 Madeira, while the final map layout was edited with Adobe® Illustrator® CS5. Photos were managed and compiled using Adobe® Photoshop® CS2.

Data availability statement

The authors confirm that the geological and geomorphological data supporting the findings of this study are available within the article and its supplementary materials.

The topographic data that support the findings of this study are openly available in https://www.regione.piemonte.it/web/temi/ambiente-territorio/territorio/infrastruttura-geografica-cartografia at http://www.geoportale.piemonte.it/geocatalogorp/index.jsp, reference numbers r_piemon:2e02fda6-24ee-45bb-a36e-a2fab030b9e1 (vector files) and r_piemon:224de2ac-023e-441c-9ae0-ea493b217a8e (DTM).

Logs of boreholes and water wells that support the findings of this study are openly available in https://webgis.arpa.piemonte.it/Geoviewer2D/.

Acknowledgements

The author thank Cecilia Furlan, Philip Hughes, Adriano Ribolini and Philippe Schoeneich for their valuable and thorough reviews and useful comments, from which we have greatly benefited in revising the manuscript and the geological map.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Gianfranco Fioraso http://orcid.org/0000-0003-1354-5424
Giovanni Monegato http://orcid.org/0000-0002-0065-1220
Gianni Balestro http://orcid.org/0000-0001-5215-4659
Irka Hajdas http://orcid.org/0000-0003-2373-2725

References

Aigotti, D., & Ratti, G. (1981). Studio geofisico di un bacino lacustre alpino. Atti 1° Convegno annuale GNGTS, 267–282.

Balestro, G., Cadoppi, P., Perrone, G., & Tallone, S. (2009b). Tectonic evolution along the Col del Lis-Trana deformation zone (internal Western Alps). *Italian Journal of Geosciences*, *128*(2), 331–339. https://doi.org/10.3301/IJG.2009.128.2.331

Balestro, G., Spagnolo, G., Lucchesi, S., Fioraso, G., Forno, M. G., Cadoppi, P., Tallone, S., Piccardo, G. B., & Polino, R. (2009a). *Carta Geologica d'Italia alla scala 1:50.000. Foglio 155 Torino Ovest*. ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale.

Bini, A., Borsato, A., Carraro, F., Carton, A., Corbari, D., Cucato, M., Monegato, G., & Pellegrini, G. B. (2004a). Definitions of terminologies used in the mapping of Quaternary deposits in the Alpine area. *Il Quaternario – Italian Journal of Quaternary Science*, *17*, 75–82.

Bini, A., Cita, M. B., & Gaetani, M. (1978). Southern Alpine lakes — hypothesis of an erosional origin related to the Messinian entrenchment. *Marine Geology*, *27*(3-4), 271–288. https://doi.org/10.1016/0025-3227(78)90035-X

Bini, A., Zuccoli, L., Bussolini, C., Corbari, D., Da Rold, O., Ferliga, C., Rossi, S., & Viviani, C. (2004b). Glacial history of the southern side of the central Alps, Italy. In J. Ehlers

& P. L. Gibbard (Eds.), *Quaternary glaciations – extent and chronology* (pp. 195–200). Elsevier.
Bortolami, G. C., Crema, G. C., Malaroda, R., Petrucci, F., Sacchi, R., Sturani, C., Venzo, S., & Zanella, E. (1969). *Carta Geologica d'Italia alla scala 1:100.000, Foglio 56 Torino (II ed.)*. Servizio Geologico d'Italia.
Braakhekke, J., Ivy-Ochs, S., Monegato, G., Gianotti, F., Martin, S., Casale, S., & Christl, M. (2020). Timing and flow pattern of the Orta Glacier (European Alps) during the Last Glacial maximum. *Boreas*, *49*(2), 315–332. https://doi.org/10.1111/bor.12427
Capeder, G. (1904). Sulla struttura dell'Anfiteatro morenico di Rivoli in rapporto alle diverse fasi glaciali. *Bollettino Società Geologica Italiana*, *23*, 4–18.
Carraro, F. (1996). Revisione del Villafranchiano nell'area-tipo di Villafranca d'Asti. *Il Quaternario – Italian Journal of Quaternary Science*, *9*(1), 5–120.
Carraro, F., & Petrucci, F. (1977). Geologia dei depositi superficiali: Anfiteatro morenico del Tagliamento. In: B. Martinis (Ed.), Studio geologico dell'area maggiormente colpita dal terremoto friulano del 1976. *Rivista Italiana Paleontologia*, *83*(2), 281–306.
Chang, K. H. (1975). Unconformity-bounded stratigraphic units. *Geological Society of America Bulletin*, *86*(11), 1544–1552. https://doi.org/10.1130/0016-7606(1975)86<1544:USU>2.0.CO;2
Charrier, G., & Peretti, L. (1973). Ricerche sull'evoluzione del clima e dell'ambiente durante il Quaternario nel settore delle Alpi occidentali italiane: IV. Tardoglaciale e Finiglaciale di Villar Dora nella bassa valle della Dora Riparia. *Allionia*, *19*, 97–143.
Charrier, G., & Peretti, L. (1975). Analisi palinologica e datazione radiometrica C14 di depositi torbosi intermorenici della regione Alpina Piemontese, applicate allo studio del clima e dell'ambiente durante il Quaternario superiore. *Bollettino Comitato Glaciologico Italiano*, *23*, 51–66.
Cossart, E., Fort, M., Bourlès, D., Braucher, R., Perrier, R., & Siame, L. (2012). Deglaciation pattern during the Lateglacial/Holocene transition in the southern French Alps. Chronological data and geographical reconstruction from the Clarée Valley (upper Durance catchment, southeastern France). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *315-316*, 109–123. https://doi.org/10.1016/j.palaeo.2011.11.017
Dahms, D. E. (2002). Glacial stratigraphy of Stough Creek basin, wind River range, wyoming. *Geomorphology*, *42*(1-2), 59–83. https://doi.org/10.1016/S0169-555X(01)00073-3
Evans, D. J. A., Ewertowski, M., Orton, C., & Graham, D. J. (2018). The glacial geomorphology of the ice cap piedmont lobe landsystem of East Mýrdalsjökull, Iceland. *Geosciences*, *8*(6), 194. https://doi.org/10.3390/geosciences8060194
Finckh, P. G. (1978). Are southern Alpine lakes former Messinian canyons? Geophysical evidence for preglacial erosion in the southern Alpine lakes. *Marine Geology*, *27*(3-4), 289–302. https://doi.org/10.1016/0025-3227(78)90036-1
Finsinger, W., & Tinner, W. (2006). Holocene vegetation and land-use changes in response to climatic changes in the forelands of the southwestern Alps, Italy. *Journal of Quaternary Science*, *21*(3), 243–258. https://doi.org/10.1002/jqs.971
Fioraso, G., & Mosca, P. (2020). *Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 171 Cesana Torinese*. ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale. 132 pp.
Gastaldi, B. (1872). Cenni sulla costituzione geologica del Piemonte. *Bollettino Regio Comitato Geologico Italiano*, *3*, 14–32.
Germani, D., Angiolini, L., & Cita, M. B. (2003). Guida italiana alla classificazione e alla terminologia stratigrafica. APAT. Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici. Quaderni Serie III, 9, 155 pp.
Gianotti, F., Forno, M. G., Ivy-Ochs, S., Monegato, G., Pini, R., & Ravazzi, C. (2015). Stratigraphy of the Ivrea morainic amphitheatre (NW Italy): an updated synthesis. *Alpine and Mediterranean Quaternary*, *28*(1), 29–58.
Hughes, P. D. (2010). Geomorphology and Quaternary stratigraphy: The roles of morpho-, litho-, and allostratigraphy. *Geomorphology*, *123*(3-4), 189–199. https://doi.org/10.1016/j.geomorph.2010.07.025
Ivy-Ochs, S., Lucchesi, S., Baggio, P., Fioraso, G., Gianotti, F., Monegato, G., Graf, A. A., Akçar, N., Christl, M., Carraro, F., Forno, M. G., & Schlüchter, C. (2018). New geomorphological and chronological constraints for glacial deposits in the Rivoli-Avigliana end-moraine system and the lower Susa Valley (Western Alps, NW Italy). *Journal of Quaternary Science*, *33*(5), 550–562. https://doi.org/10.1002/jqs.3034
Larocque, I., & Finsinger, W. (2008). Late-glacial chironomid-based temperature reconstructions for Lago Piccolo di Avigliana in the southwestern Alps (Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *257*(1-2), 207–223. https://doi.org/10.1016/j.palaeo.2007.10.021
Martinetto, E., Scardia, G., & Varrone, D. (2007). Magnetostratigraphy of the Stura di Lanzo fossil forest succession (Piedmont, Italy). *Rivista Italiana di Paleontologia e Stratigrafia*, *113*(1), 109–125.
Martins, C., & Gastaldi, B. (1850). Essai sur les terrains superficiels de la Vallée du Pô, aux environs de Turin, comparés à ceux de la plaine Suisse. *Bulletin Société Géologique France*, *7*, 554–605.
Mattirolo, E., Novarese, V., Franchi, S., & Stella, A. (1913). *Carta Geologica d'Italia alla scala 1:100.000, Foglio 55 Susa*. Regio Ufficio Geologico.
Mattirolo, E., Novarese, V., Franchi, S., Stella, A., & Sacco, F. (1925). *Carta Geologica d'Italia alla scala 1:100.000, Foglio 56 Torino (I ed.)*. Regio Ufficio Geologico.
Monegato, G., Ravazzi, C., Donegana, M., Pini, R., Calderoni, G., & Wick, L. (2007). Evidence of a two-fold glacial advance during the last glacial maximum in the Tagliamento end moraine system (eastern Alps). *Quaternary Research*, *68*(2), 284–302. https://doi.org/10.1016/j.yqres.2007.07.002
Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., & Piccin, A. (2017). The Alpine LGM in the boreal ice-sheets game. *Scientific Reports*, *7*(1), 2078. https://doi.org/10.1038/s41598-017-02148-7
North American Commission on Stratigraphic Nomenclature (NACSN). (1983). North American stratigraphic code. *AAPG Bulletin*, *67*(5), 841–875.
Ognibeni, T., & Venzo, S. (1951). Indagini geologiche e geotecniche per l'impostazione di diga in terra e serbatoio idrico nella zona di Moiola (Valle Studa di Demonte – Cuneo). *Rivista di Ingegneria*, *10*, 3–12.
Passchier, S., Laban, C., Mesdag, C. S., & Rijsdijk, K. F. (2010). Subglacial bed conditions during Late Pleistocene glaciations and their impact on ice dynamics in the southern North Sea. *Boreas*, *39*, 633–647. https://doi.org/10.1111/j.1502-3885.2009.00138.x
Penck, A., & Brückner, E. (1909). Die Alpen im Eiszeitalter. Tauchnitz Ed., Leipzig, 3 vol., 1199 pp.

Petrucci, F. (1970). Rilevamento geomorfologico dell'Anfiteatro morenico di Rivoli-Avigliana. *Memorie Società Italiana Scienze Naturali*, *18*(3), 95–124.

Piana, F., Barale, L., Compagnoni, R., d'Atri, A., Fioraso, G., Irace, A., Mosca, P., Tallone, S., Monegato, G., & Morelli, M. (2017a). Geological map of Piemonte Region at 1:250,000 scale explanatory notes. *Accademia Scienze Torino, Memorie Scienze Fisiche*, *41*, 3–143.

Piana, F., Fioraso, G., Irace, A., Mosca, P., d'Atri, A., Barale, L., Falletti, P., Monegato, G., Morelli, M., Tallone, S., & Vigna, G. B. (2017b). Geology of Piemonte region (NW Italy, Alps-Apennines interference zone). *Journal of Maps*, *13*(2), 395–405. https://doi.org/10.1080/17445647.2017.1316218

Polino, R., Borghi, A., Carraro, F., Dela Pierre, F., Fioraso, G., Gattiglio, M., & Giardino, M. (2002). *Carta Geologica d'Italia alla scala 1:50.000, Foglio 132-152-153 Bardonecchia*. Servizio Geologico d'Italia.

Preusser, F., Reitner, J. M., & Schlüechter, C. (2010). Distribution, geometry, age and origin of overdeepened valleys and basins in the Alps and their foreland. *Swiss Journal of Geosciences*, *103*(3), 407–426. https://doi.org/10.1007/s00015-010-0044-y

Prever, P. L. (1907). Sulla costituzione dell'anfiteatro di Rivoli in rapporto con le successive fasi glaciali. *Memorie Reale Accademia Scienze Torino*, *58*, 301–333.

Räsänen, M. E., Auri, J. M., Huitti, J. V., Klap, A. K., & Virtasalo, J. J. (2009). A shift from lithostratigraphic to allostratigraphic classification of Quaternary glacial deposits. *GSA Today*, *19*(2), 4–11. https://doi.org/10.1130/GSATG20A.1

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., … Talamo, S. (2020). The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon*, *62*(4), 725–757. https://doi.org/10.1017/RDC.2020.41

Sacco, F. (1887). L'anfiteatro morenico di Rivoli. *Bollettino Regio Comitato Geologico Italiano*, *18*(5-6), 141–180.

Sacco, F. (1921). Il glacialismo della Valle di Susa. *L'Universo*, *2*(8), 561–592.

Salvador, A. (1994). *International stratigraphic guide: A guide to stratigraphic classification, terminology and procedure, 2nd ed.* International Union of Geologic Sciences and The Geological Society of America. 214 pp.

Seguinot, J., Jouvet, G., Huss, M., Funk, F., Ivy-Ochs, S., & Preusser, F. (2018). Modelling last glacial cycle ice dynamics in the Alps. *The Cryosphere*, *12*(10), 3265–3285. https://doi.org/10.5194/tc-12-3265-2018