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ORIGINAL PAPER

The hidden glacial landscape of the Monti della Laga (central Apennines, Italy)

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Abstract
The geological and geomorphological record of the Last Glaciation in the Apennines is extensively documented, except for the Monti della Laga sector, where limited indicators of glacier extension have been reported. This study presents field evidence of glacial deposits and landforms from two specific sites within the Monti della Laga Range: Monte Pelone and Tordino Valley head. Although limited, this evidence suggests glaciation within a structural and lithological setting that facilitated rapid slope evolution. The post-glaciation paraglacial processes in the area erased most glacial traces, but our geomorphological and stratigraphical investigations identified specific landforms of glacial origin. Notably, at Monte Pelone, a semi-circular depositional landform exhibiting a significant presence of coarse clasts and distinctive rotational features has been identified as a moraine. Additionally, a smaller moraine ridge with evidence of diamicton deposition was observed in the Tordino Valley head. These observations align with an Equilibrium Line Altitude estimated at 1750 m a.s.l. in the central Apennines in the Last Glacial Maximum and, considering the favourable topographic conditions of the area, significantly contribute to the understanding of glaciations within the central Apennines.

Keywords Glacial geomorphology · Monti della Laga · Last glaciation · Central Apennines · Italy

1 Introduction

Traces of Last Glacial Maximum (LGM) glaciations in the central Apennines are well documented, whereas evidence of earlier glacial events remains scarce (Jaurand 1999; Giraudi et al. 2004; Ribolini et al. 2022). Interest in this topic dates to the early twentieth century (Saint–Robert and Berruti 1871) but surged in the 1930s, offering the first detailed qualitative descriptions of Apennine glaciations (Suter 1934, 1939; Sestini 1940). Recent studies have extensively investigated the central Apennines glaciations, providing detailed chrono sequences for select sites and insights into deglaciation dynamics and processes (Federici 1979; Jaurand 1999; Giraudi and Frezzotti 1997; Giraudi et al. 2004; Giraudi 2012).

Most Apennine glaciers developed within northward-oriented valleys, with exceptions of very few east and south-facing valleys (e.g., Majelama in the Velino-Sirente Range) (Giraudi 1995; Giraudi et al. 2004). In the Gran Sasso Massif, the record of three glaciations tentatively dated at Middle and Late Pleistocene was identified, and the LGM's maximum expansion occurred at 27.000 years BP (Giraudi and Frezzotti 1997; Giraudi 2012). Studies in the Mount Terminillo and Maiella massifs reconstructed LGM glacier positions and identified frontal moraines (Giraudi 1998a; Jaurand 1999), while LGM glacial deposits were detected in the Campo Felice area and Majelama within the Monte Velino Massif (Giraudi et al. 2011; Giraudi 1995). Additionally, remains of an LGM frontal moraine system were described in the Aremogna plain close to Monte Greco Massif (Frezzotti and Giraudi 1989). The Equilibrium Line Altitude (ELA) during the LGM is estimated at around 1750 m a.s.l. in the central Apennines (Federici 1979), suggesting extensive glacier coverage, including the Monti della Laga. Although strongly eroded, Suter (1934) reported traces of glacial landforms between Monte Gorzano and Pizzo di Sevo. While Federici (1979) mentioned generic glacial deposits on Monti della Laga, Dramis et al. (1987) observed and mapped glacial deposits, cirques, and periglacial landforms in the Monte Pelone area. Jaurand (1999)

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identified several glacial cirques and traces of moraine ridges on the eastern flank of Monti della Laga but lacked detailed field evidence and deposit descriptions.

The geomorphological and stratigraphical investigations of this work highlights the rapid paraglacial evolution of the Monti della Laga area, allowing the preservation of glacial deposits and landforms during fieldwork and offering new insights into the Late Pleistocene central Apennine glaciations.

2 Geography and climatic setting

The Monti della Laga are located in the central Apennines between Abruzzo, Marche and Lazio regions and are included in the Parco Nazionale del Gran Sasso e Monti della Laga (Fig. 1). The massif is N-S oriented, stretches for about 20 km, and borders the Sibillini Mountains to the N, the Gran Sasso Massif to the S, and the Amatrice Basin to the W. The mountain range has several peaks that exceed 2000 m a.s.l., from N to S Monte Macera della Morte (2073 m), Pizzo di Sevo (2419 m), Cima Lepri (2445 m), Pizzo di Moscio (2411 m), Monte Pelone (2259 m), Monte Gorzano (2458 m), Cima della Laghetta (2369 m) and Monte di Mezzo (2155 m) (Figs. 1 and 2). The area's climate is typically Mediterranean, characterised by dry summers with precipitation peaks in spring and autumn. Intense rainfall and snowfall are frequent during winter and spring. The annual average precipitation is about 900 mm (data from the Amatrice weather station, 955 m a.s.l.; 1951–2015 timeframe) with a mean annual temperature of 10.3 °C. Above 2000 m a.s.l., the climate is characterised by lower temperatures with prolonged frost in winter for 5-6 months and a snow cover for more than 6 months a year (Petriccione and Bricca 2019).

3 Geological, structural, and geomorphological background

The Monti della Laga geology is characterised by a siliciclastic foreland succession developed from late Tortonian to late Messinian, during eastward migration of the fold and thrust belt Apennines due to the westward subduction of the continental Adriatic Plate beneath the European Plate (Carminati et al. 2004; Milli et al. 2009; Marini et al. 2015). The Monti della Laga has a triangular shape and is bordered to the S by the Gran Sasso thrust

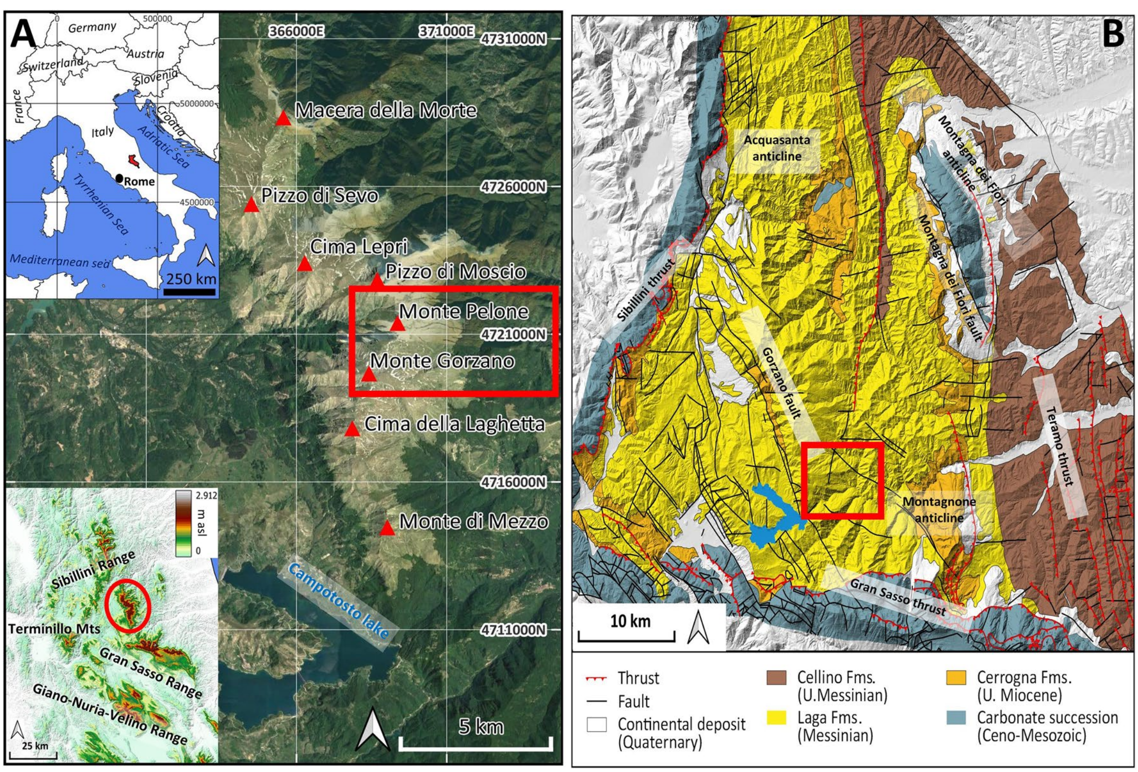

Fig. 1 **A** Google Earth™ image of the Monti della Laga area (the red square indicates the study area). In the upper left corner, the borders of Parco Nazionale del Gran Sasso e Monti della Laga, and in the down-left the position of the main chains that bounded the study area and the Monti della Laga (red circle). **B** Geological and structural map of the Monti della Laga redrawn from Centamore et al. (1992) and Milli et al. (2009). The red square is the study area

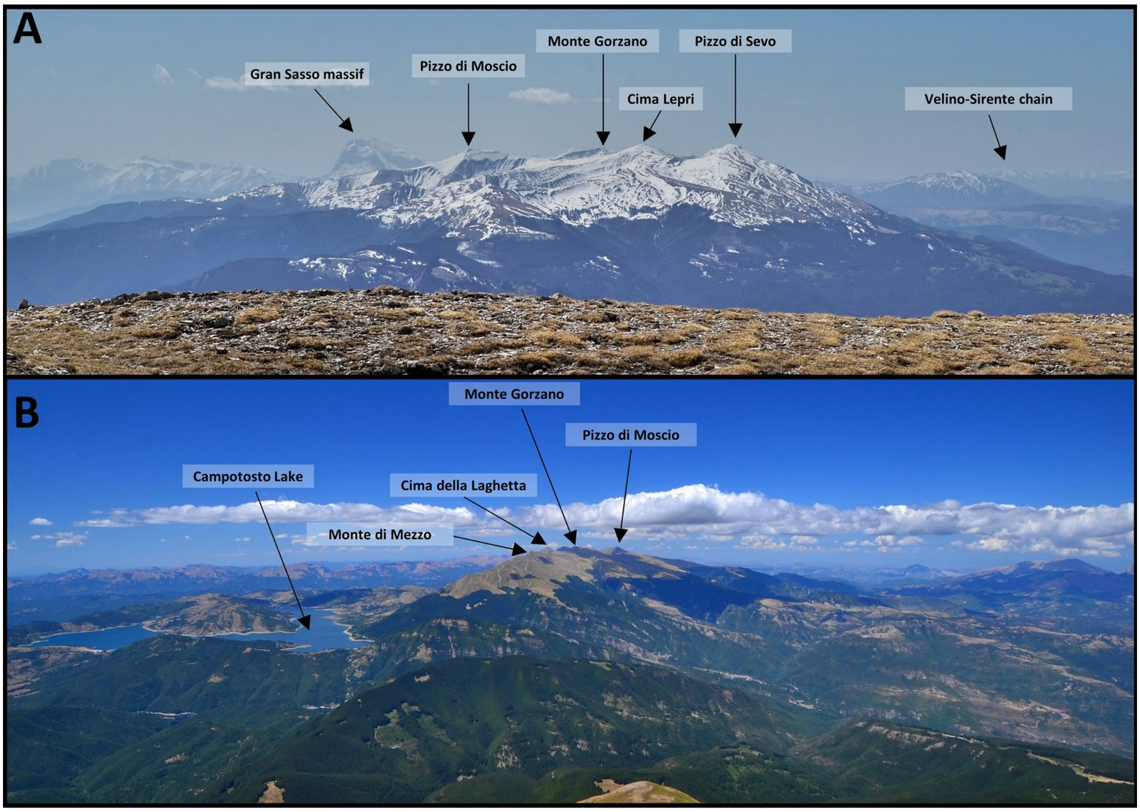

Fig. 2 **A** Panoramic view from the Monte Vettore towards the south indicating the main peaks of Monti della Laga, the Gran Sasso Massif and the Velino-Sirente chain. **B** Panoramic view from the Gran Sasso towards the north, where the prominent peaks of Monti della Laga are reported (photos: L. Forti)

front, to the W by the Monti Sibillini thrust, and to the E by the Montagna dei Fiori-Montagnone anticline (Centamore et al. 1991; Bigi et al. 2011). The structural setting of the Monti della Laga is connected to N–S trending thrusts-related Monte Gorzano-Acquasanta and Montagna dei Fiori-Montagnone anticlines (Bigi et al. 2011; Milli et al. 2009) (Fig. 1B). Following the eastward compressional stage, an extensional phase started in the late Pliocene-early Pleistocene with the onset of NW–SE trending normal faults (Cosentino et al. 2010; Bigi et al. 2011) that are still active today, as indicated by the seismicity recorded by the August 2016 and January 2017 earthquakes in (Amatrice, Mw 6.0, and Campotosto Mw 5.4, respectively). The stratigraphic succession is composed by silico-clastic turbidite deposits of Laga Formation (mainly alternation of sandstone and mudstone strata) subdivided into three main units (Laga 1, Laga 2 and Laga 3) that recorded the easternmost migration of the Apennines foredeep over the Montagna dei Fiori-Montagnone anticline (Milli et al. 2009; Marini et al. 2015) (Fig. 1B).

Dramis et al. (1987) carried out the first geomorphological survey of the area, highlighting a strong morpho-structural influence on the topography affecting the geomorphological processes (e.g. slope processes). The authors also detected glacial landforms and deposits at the highest elevations and periglacial processes/deposits at lower elevations (1700–2100 m a.s.l.) (Dramis et al. 1987).

4 Methods

This work is based on a geomorphological and geological field and remote survey. This preliminary work was performed through QGIS 3.20 open-source software, analysing orthophoto datasets (Abruzzo Region 2010 aerial orthophotographs and high-resolution Google™ satellite imagery; NextGis 2021). Contour lines at 25 m equidistance and hillshade were derived and used for landform interpretation from Italy’s Digital Elevation Model (DEM) (Tarquini et al. 2007). A field survey was conducted only in the highest part of the Monti della Laga Range (approximately above 1800 m a.s.l.) (Fig. 2), focusing on its eastern slope where the glacial evidence is better preserved due to the less active slope dynamics.

Field survey allowed a detailed mapping of the area and the description of deposits and landforms, validating the geomorphological features initially recognised through remote sensing analysis. Considering that the study area is within the Parco Nazionale del Gran Sasso e Monti della Laga and protected by national laws, we investigated only the natural outcrops exposed by ongoing erosive processes.

5 Results

The combined remote sensing and field survey enabled us to characterise the area's overall geomorphological context, emphasising extensive slope and fluvial processes. Nonetheless, within this broader context, our investigations pinpointed two distinct sites with evidence of preserved past glacial features: a cirque located on the southeast slope of Monte Pelone Peak and a deposit within the Tordino Valley head, just north of Monte Gorzano (Fig. 3).

5.1 Monte Pelone area

Monte Pelone's southeastern slope is dominated by gravitational, fluvial, and snow-melting processes that model the present-day landscape. The field survey focused on the cirque-shaped escarpment and valley head 500 m south of the Monte Pelone Peak (Figs. 3A and 4). It originated from the area's morpho-structural setting (Dramis et al. 1987) with ongoing fluvial slope processes.

Upslope, the cirque is characterised by slope deposits dissected by water streams. Downslope, a convex, semi-circular landform dams the valley, creating an NNE steep external slope (Fig. 4).

This landform generated a small sedimentary trap, filled by slope and fluvial deposits, which currently form the slightly sloping cirque floor (Fig. 4). At the edge, between the cirque floor and the external slope, the main semi-circular sedimentary body is topped by a smaller semi-circular landform consisting of a sedimentary ridge with an asymmetric triangular section (Fig. 4). This smaller ridge and the main sedimentary body are incised by two seasonal water courses and partly eroded by minor, superficial landslides, and sheet/rill erosion. The stream channels are active during snow melting, and intense rainfall erodes the cirque floor deposits, forming small erosional terraces (Fig. 4).

The external slope (toward NNE) shows several tilted boulders whose inclination did not follow the direction of the slope. Two profiles P1 on the cirque floor and P2 on the top of the smaller semi-circular ridge (Fig. 4) were identified. P1 consists of fine to very fine massive sands with very rare dispersed fine gravels (Fig. 5A, C) while P2 consists of a clast-supported massive diamicton made of sand and gravel (sandstone of Laga Formation). The gravelly clasts in P2 are monogenic (Laga Formation), unsorted and platy angular. They are generally unweathered, but some displayed a slightly reddish superficial weathering cortex (Fig. 5D).

5.2 Tordino valley head area

On the northeastern slope of Monte Gorzano, the head of the Tordino Valley is above 2000 m a.s.l. (Fig. 3B). The main morphological features are ephemeral stream channels and escarpments, aligned along minor E-W tectonic lineaments (Dramis et al. 1987), suggesting that structural factors control the valley head. Like the Monte Pelone cirque, the valley head has undergone considerable erosion due to gravitational slope and surface runoff processes. The valley flanks are characterised by slope dynamics resulting in the accumulation of gravitative and colluvial deposits, thickening

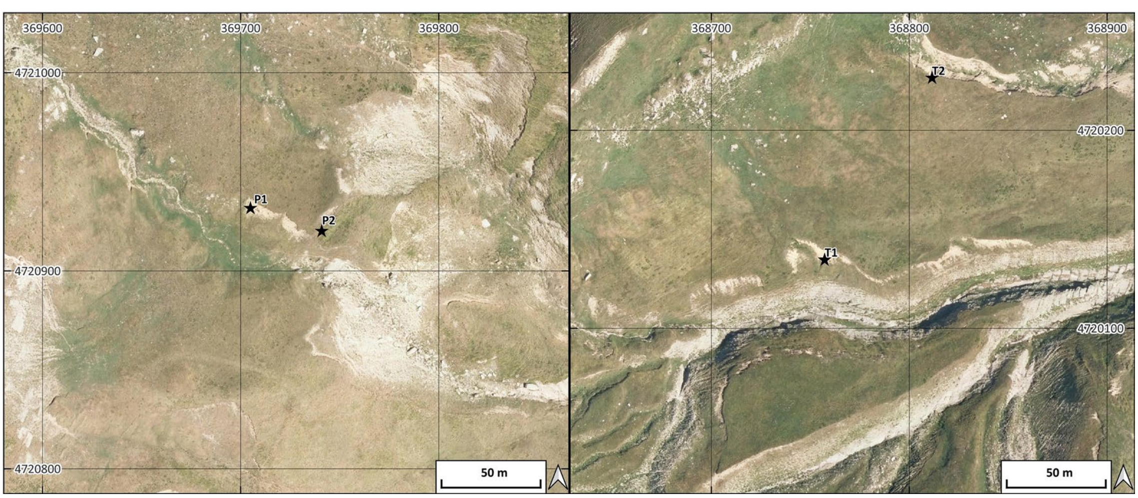

Fig. 3 The study areas: **A** Google Earth™ imagery of the Monte Pelone area. **B** Google Earth™ imagery of the Tordino Valley head

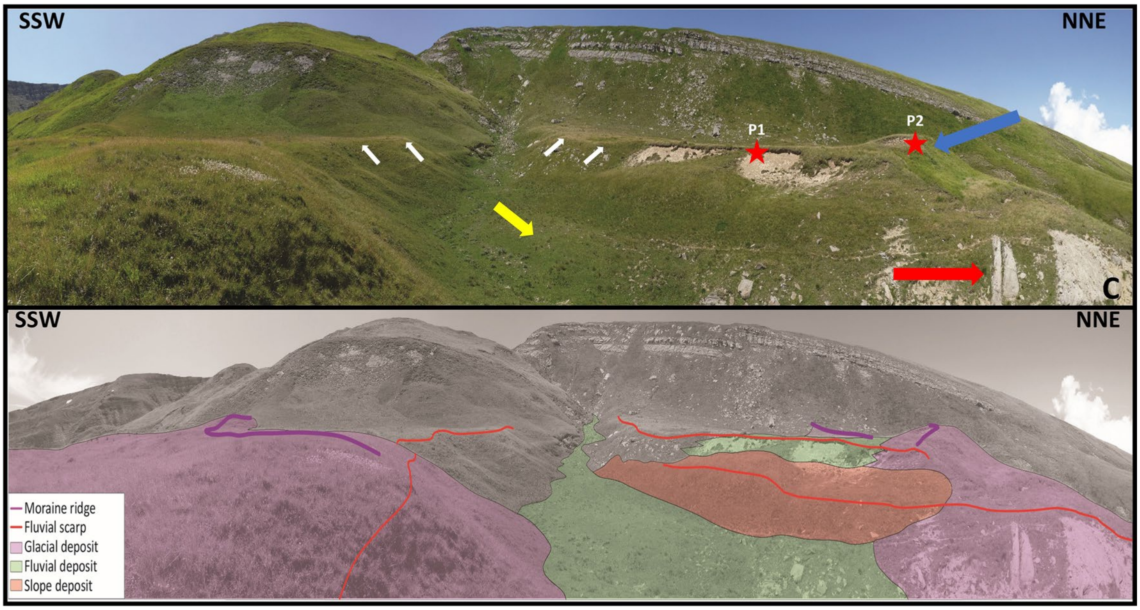

Fig. 4 **A** Panoramic view of the Monte Pelone cirque, the red stars highlight the position of the P1 and P2 profiles. The blue arrow is the triangular ridge, the red is the tilted block, the yellow is the valley floor, and the white arrow is the fluvial escarpment. **B** Line drawing of the glacial evidence recognised in the Monte Pelone area

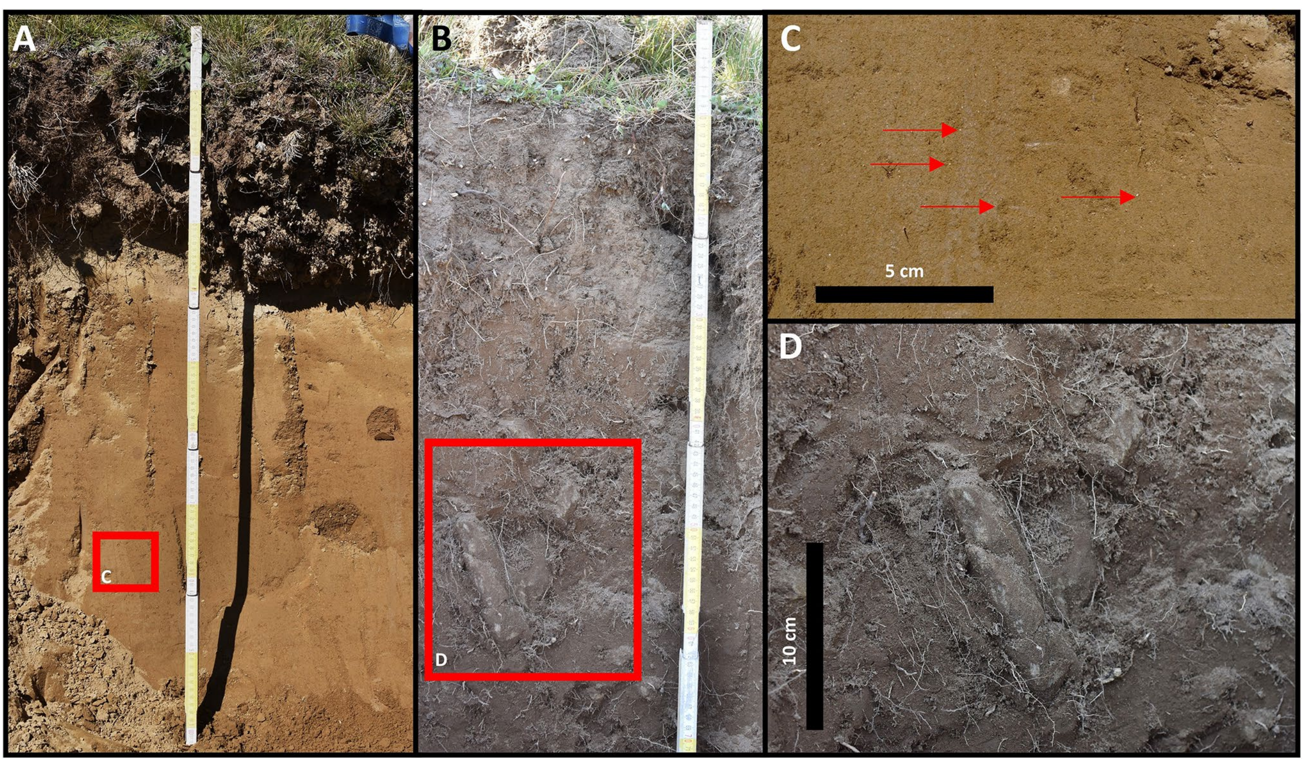

Fig. 5 Pictures of P1 (**A**) and P2 (**B**) profiles. **C** Detail of P1 showing fine gravel clast dispersed in the fine matrix (red arrows). **D** Detail of sandstone clasts

at foot slopes (Fig. 6). The southern valley flank features are characterised by numerous smaller valleys occupied by debris flow deposits originating from the steep N-E slope of Monte Gorzano. Conversely, the northern slope can be

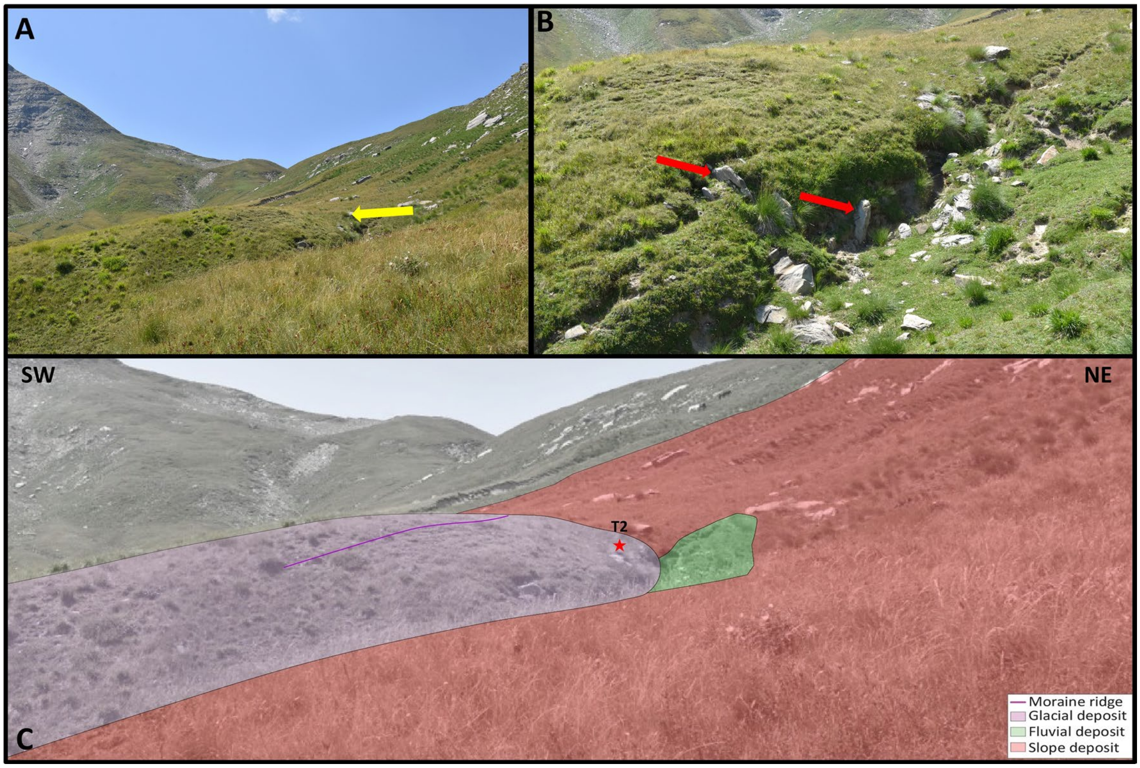

Fig. 6 Tordino Valley head area. **A** Small counterscarp on N slope of Tordino Valley head (yellow arrow) and **B** tilted clasts (red arrows). **C** Line drawing of the glacial evidence recognised in the Tordino Valley head

divided into three parts: an upslope area characterised by bare bedrock and slope deposits, a toe slope displaying a gentle topography with erosional fluvial escarpment with a thin sedimentary cover, and a steeper midslope with a thicker sedimentary sequence, partially eroded by streams (Fig. 6C).

Notably, between 2100 and 2130 m a.s.l., the slope gradient changes due to several tilted clasts forming a slight counterscarp (Fig. 6A, B). Within the valley, the stream erosion has exposed several stratigraphic profiles focused on investigating the thickest profiles, T1 and T2 (Fig. 3). T1, positioned along the left side of the valley (Fig. 3), displays poorly cross-laminated locally massive medium to fine sand with scattered sandstone clasts (Fig. 7A, B). T2, located on the northern slope, reveals a 4.30 m-thick succession of four sedimentary units (Fig. 7C, D). Unit 1, from top to 160 cm, is made of fine to medium sand with poorly evident layering parallel to the slope. Unit 2, from 160 to 210 cm, consists of fine to very fine gravel and sands with occasional cm-sized clasts and a more pronounced slope-parallel lamination. Unit 3, spanning from 210 to 250 cm, is made of chaotic pebbles and gravels in a sandy-silt matrix (diamicton) and displays an evident undulating erosion surface at the base. Finally, Unit 4, from 250 to 430 cm, comprises a medium to fine sand matrix displaying well-defined lamination, oriented sandstone clasts parallel to the slope, and weathered sandstone cobbles.

6 Discussion

Given the altitudinal and topographical settings of our study area, we consider the existence of extensive glacier coverage in both the Tordino Valley and the Monte Pelone area. These areas display topoclimatic conditions and elevations favourable to the glacier occurrence.

The geomorphological investigation at Monte Pelone reveals distinctive features in the semi-circular sedimentary deposits and the smaller ridge associated with the P2 profile. We interpret this evidence as a glacial deposit, specifically an ablation till. Therefore, this deposit displays a massive, heteromeric nature, characterised by several tilted blocks that constitute a semi-circular frontal moraine (Figs. 4, 5 and 8A).

Therefore, evidence of glacial landforms and deposits in the Tordino Valley head occurred above the 2100 m a.s.l. On the valley's northern mid-slope, a slight counterscarp with tilted clasts (Figs. 6, 7 and 8B) is evidence of a lateral moraine. This landform is partially eroded and buried by colluvial and slope deposits today. Although the tilted

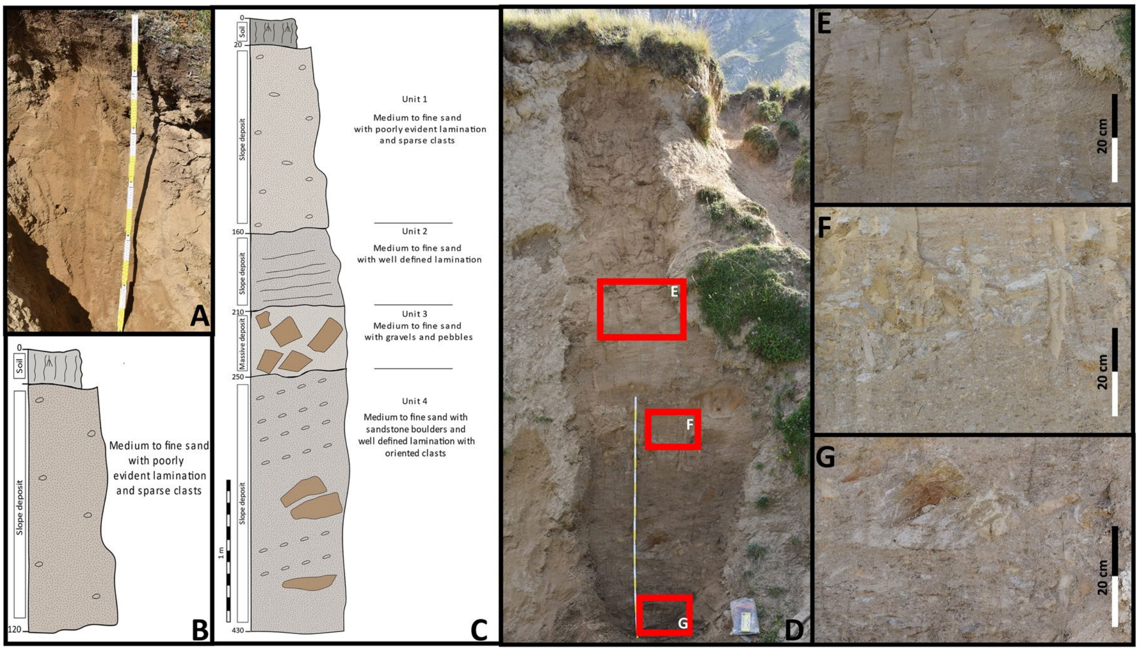

Fig. 7 Tordino Valley head. In **A** and **B** T1 stratigraphic sequence. **C, D** Stratigraphic log and orthophoto of T2 sequence where the main sedimentary elements were reported. **E** Detail of the chaotic organisation within Unit 3 debris flow layer. **E–F** Details of Unit 4 where the alignments of clasts (**F**) and the boulders were highlighted (**G**)

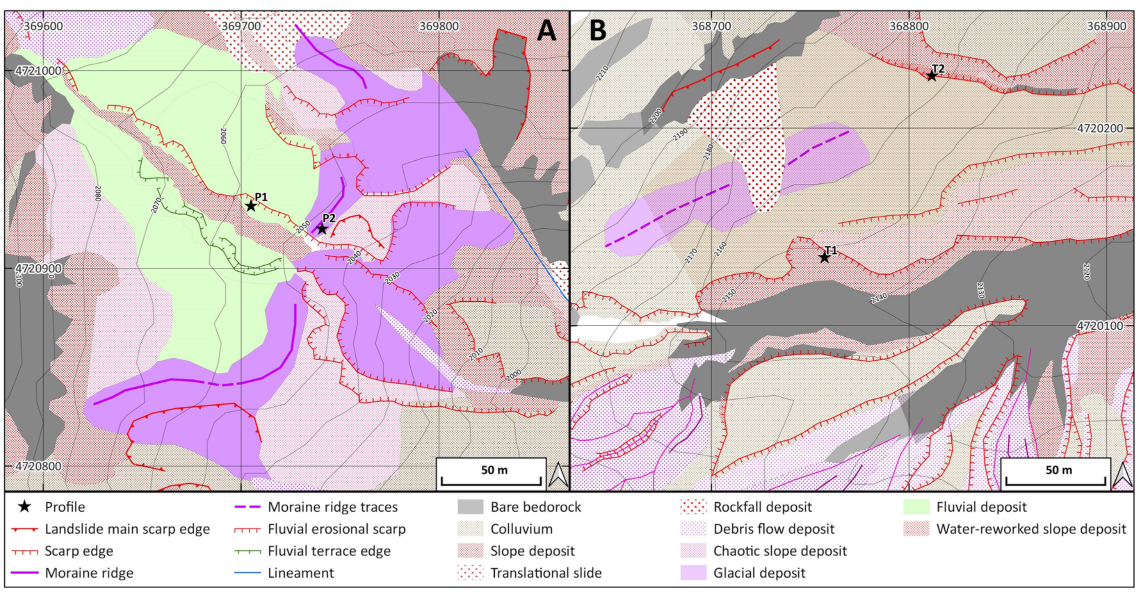

Fig. 8 Geomorphological sketch of the Monte Pelone (**A**) and the Tordino Valley head (**B**) where the glacial evidence is reported. The area is the same as in Fig. 3

clasts could be interpreted as the results of gravitative-slope processes, in our case, the geomorphological and topo-climatic context suggest a possible glacial origin for this feature.

T2 profile provides the record to reconstruct the geomorphological evolution and dynamics of the Tordino Valley head. From the bottom to the top, Unit 4 is slope deposits, unconformably buried by Unit 3 typical of a margin-glacial mass-transport possibly deposited within a small lateral basin between the valley slope and an ice mass. Units 2 and 1 consist of colluvial deposits partially derived by the erosion of Unit 3 (Fig. 7). T2 suggests the occurrence of a slope deposition followed by the advance of a valley glacier, as indicated by the presence of the margin-glacial deposits of Unit 3. The end of the glacial condition, increased water availability, and heightened gravitational slope processes and concurrently, extensive fluvial network readjustment occurred due to significant neo-tectonic activity (Galli and Galadini 2000), with upstream migration of fluvial knickpoints, enhancing the fluvial incision, erosion rates and slope processes. This resulted in the local erosion of Unit 3 deposits and the deposition of colluvial deposits, reaching up to 3 m in thickness (Units 2 and 1). The geomorphological analyses added more field information on the glacial observations made by Jaurand (1994) and Dramis et al. (1987) in the area between Pizzo di Moscio and Monte Gorzano. Therefore, it is evident that following the glacial retreat, the glacial landforms, and deposits in the Laga Mountains were subjected to heavy erosion and consequently scarce preservation. However, this does not occur in the Gran Sasso area, where both substrate geology and landforms have enabled the preservation of numerous glacial traces (Giraudi and Frezzotti 1997 among others). Despite a similar topo-climatic context that is prone to the presence of a past glaciation like the one that occurred in the Gran Sasso Massif, the sparse occurrence of glacial deposits and landforms in the Monti della Laga may be caused by widespread paraglacial processes that have sculpted the landscape after deglaciation. The siliciclastic sequence of the Laga Formation and the morpho-structural setting of the Monti della Laga Massif favours the enhancement of erosion processes onset after the glacier retreat. The alternation of sandstone and mudstone of the Laga Formation and their dipping in the direction of the slope favoured more intensive slope processes (toppling, sliding, and deep-seated gravitational slope processes) than the limestones sequence of Gran Sasso, preventing the preservation of deposits. These findings require further field studies to analyse glacial landforms and deposits, including quantitative dating. Additionally, it would be valuable to investigate landforms at lower altitudes (below the estimated Equilibrium Line Altitude), where paraglacial processes are likely less intense due to gentler slopes.

7 Conclusions

Based on estimates of the Equilibrium Line Altitude (ELA) at 1750 m a.s.l. during the Last Glacial Maximum (LGM) in the central Apennines, along with the maximum LGM glacier advance at 1580 m a.s.l. (22,600 years B.P.) in the Gran Sasso area and considering the topo-climatic conditions, we highlight evidence of glaciation episodes within the Monti della Laga Range. Detailed geomorphological and stratigraphic investigations have documented glacial deposits and landforms at two specific locations: i) Monte Pelone where a semi-circular depositional landform displaying a significant presence of coarse clasts and distinctive rotational features has been identified as a moraine; ii) Tordino Valley head where a smaller moraine ridge exhibiting evidence of diamicton deposition. Despite limitations, this evidence suggests past glaciation occurred within a geological and structural context that facilitated rapid slope evolution. Post-glacial paraglacial processes in the area have largely erased most glacial traces, particularly at higher altitudes (above 2000 m a.s.l) in the Monti della Laga Range. These detailed geomorphological and stratigraphical investigations significantly contribute to our understanding of past glaciations in the central Apennines, specifically highlighting the nature and extent of glacial activity within the Monti della Laga Range and enhancing our knowledge of glaciations in this region.

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Data availability Data will be made available upon reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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