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Late Quaternary evolution of the sedimentary environment in Modrejce near Most na Soči (Soča Valley, Julian Alps)

Poznokvartarni razvoj sedimentacijskega okolja v Modrejcah pri Mostu na Soči (Posočje, Julijske Alpe)

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Ključne besede: poledenitev, glaciofluvialna sedimentacija, glaciolakustrični sedimenti, til, Soški ledenik, kvartar, Posočje

Abstract

Geomorphological and geological mapping have long been used to study the glacial history of the Slovenian Alps, but many uncertainties remain regarding the time and extent of Pleistocene glaciations there. Glacial landforms and undisturbed glacial deposits are rare in the areas of the former glacier terminus, especially in the Soča Valley, where large discrepancies in the interpretation of the extent of the former Soča Glacier have been reported. Early studies proved inconclusive as to whether one or two glaciations extended into the Soča Valley as far as Most na Soči. In order to answer this question, the Quaternary sedimentary succession and landforms in the Modrejce Valley near Most na Soči were investigated. New geological and geomorphological field data allow the interpretation of the sedimentary environment and the stratigraphic relationships between different units. In response to glacial dynamics, the sedimentation developed from glaciofluvial and glaciolacustrine to fully glacial environments, followed by slope deposition. At higher altitudes lateral moraines are preserved, while the staircase-like slope below has been carved into older glacial, glaciofluvial and glaciolacustrine deposits by glacial and post-glacial processes, including fluvial erosion and slope dynamics. We conclude that the succession studied here was deposited over the course of two different glacial advances – LGM and pre-LGM. Our study thus suggests that the Soča Glacier extended as far as the area of Most na Soči twice over the course of the late Quaternary.

Izvleček

Geomorfološke in geološke raziskave zgodovine poledenitev v Slovenskem Alpskem prostoru imajo dolgo tradicijo, kljub temu pa še vedno ostaja več nejasnosti o obsegu in času pleistocenskih poledenitev v tem prostoru. Ledeniške geomorfne oblike in nepredelani ledeniški sedimenti so redko ohranjeni na območjih nekdanjih ledeniških čel, kar še posebej velja za Posočje, za katero so bile poročane različne interpretacije obsega nekdanjega Soškega ledenika. Pretekle študije niso uspele ugotoviti, ali je ena ali morda več poledenitev segalo tako daleč po Posočju, da je doseglo Most na Soči. Da bi raziskali to vprašanje, smo svojo študijo usmerili na kvartarno sedimentacijsko zaporedje in geomorfne oblike v Modrejcah pri Mostu na Soči. Novi terenski geološki in geomorfološki podatki omogočajo interpretacijo sedimentacijskega okolja in stratigrafskih odnosov med različnimi enotami. V povezavi z ledeniško dinamiko se je sedimentacijsko okolje razvilo iz glaciofluvialnega in glaciolakustričnega v ledeniškega, kateremu je sledilo odlaganje pobočnega materiala. Bočne morene so ohranjene na višjih legah, medtem ko je stopničasto pobočje vrezano v starejše ledeniške, glaciofluvialne in glaciolakustrične sprijete sedimente. Vrezovanje je rezultat delovanja mlajših ledeniških procesov in procesov po umiku ledenika, kot so rečna erozija in pobočna dinamika. Sklepamo, da je bilo preučeno sedimentacijsko zaporedje odloženo med dvema različnima napredovalnima fazama; v zadnjem poledenitvenem višku in v enem izmed prejšnjih. Naša študija tako nakazuje, da je Soški ledenik v poznejšem delu kvartarja dvakrat segal do območja Mosta na Soči.

Introduction

The glacial history of the southeastern Alps covers multiple glaciations, which were first established by Penk & Brückner (1901–1909). Improvements in dating methods allowed for better characterization of the chronology of the last glacial cycle (Monegato & Ravazzi, 2018), especially for the Last Glacial Maximum (LGM), which is best preserved due to its young age (about 26–19 ka, e.g., Monegato et al., 2007; Ivy-Ochs et al., 2008; Ivy-Ochs, 2015; Monegato et al., 2017). In the Alps, deposits related to older glaciations are difficult to date (e.g., Dehnert et al., 2012; Lowick et al., 2015; Rades et al., 2016) and their relative chronologies are inferred through their stratigraphic relationship with the alluvial-coastal stratigraphy (Fontana et al., 2010) or through analysis of their boundaries, which are sometimes characterized by paleosoils or peat layers (Gianotti et al., 2015).

The Alps in Slovenia hosted three large valley glaciers – the Soča, Sava Dolinka and Sava Bohinjka glaciers – as well as small cirque and valley glaciers in the Kamnik-Savinja Alps and the Karavanke Mountains (Bavec & Verbič, 2011) (Fig. 1). Small ice caps independent from the major Alpine valley glaciers were present in the Northern Dinaric sector (Žebre et al., 2013, 2016). Although the glacial history of the Slovenian territory has been studied since the late 19th century, many uncertainties remain about the timing and extent of Pleistocene glaciations in the Slovenian Alps (Bavec & Verbič, 2011; Ferk et al., 2017). This is especially true for the Soča mountain basin, where spatially incomplete records on landforms and lack of geochronological data still do not allow us to make any thorough reconstructions of former ice limits. In fact, earlier studies suggested that during the Würm (sensu Chaline & Jerz, 1984) the Soča Glacier extended southwards out of the Julian Alps down to Tolmin and even further, to Most na Soči (Brückner, 1891; Tellini, 1898; Penck & Brückner, 1901–1909; Feruglio, 1925; Winkler, 1931; Melik, 1954; Šifrer, 1965). On the other hand, more recent findings suggest that the Soča Glacier did not even reach

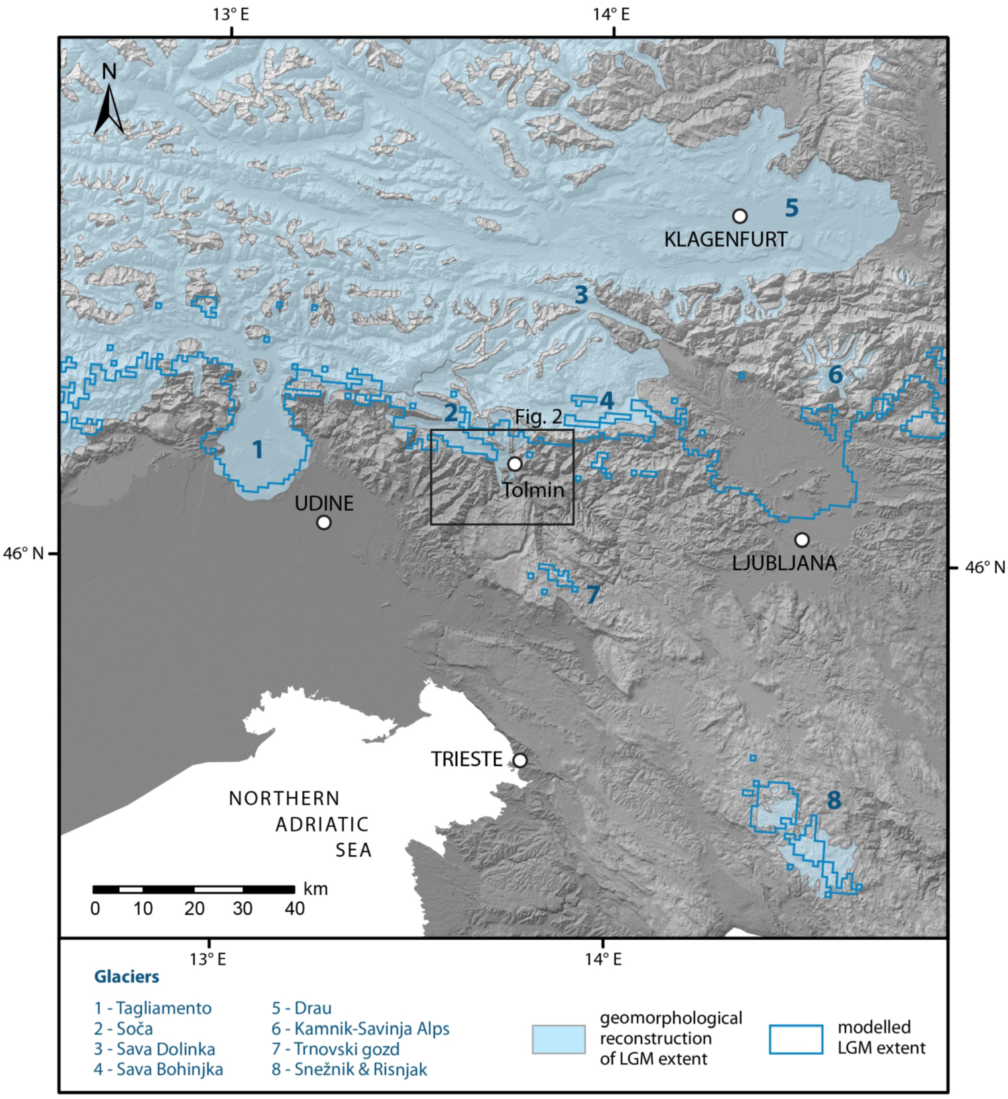

Fig. 1. LGM glacier extent in southeastern European Alps. The extent of the modelled LGM glacier driven by the EPICA paleo-temperature record and paleo-precipitation correction is after Seguinot et al. (2018), while the geomorphological reconstruction of the extent of the LGM glacier is modified from Ehlers et al. (2011). The digital terrain model is from SRTM data (Shuttle Radar Topography Mission), accessible from EarthExplorer (https://earthexplorer.usgs.gov/).

beyond the Bovec Basin, which is located more than 30 km upstream from Most na Soči (Bavec et al., 2004). Such large discrepancies are the result of sparse landform records as well as the overprinting of glacial evidence by subsequent glacier re-advances and late- to post-glacial slope processes. Moreover, the most up-to-date model-based simulations of the LGM ice extent in the Eastern Alps, including the Slovenian Alps (Seguinot et al., 2018) (Fig. 1), are not in accordance with the roughly defined geomorphological ice limits, which makes interpretation of the extent of paleo-glaciers here even more questionable and in need of new data.

In the past, glacial and proglacial sediments in the Soča Valley were studied using geological and geomorphological methods to constrain the extent of the glacier and interpret its dynamics (Šifrer, 1964/1965; Kuščer et al., 1974; Kunaver, 1975, 1980; Bavec et al., 2004). Glacial deposits from the last and penultimate glaciations were dated in the Bovec Basin (Bavec et al., 2004). Quaternary deposits in the Most na Soči area have been studied previously by Šifrer (1965) and more recently mapped by Buser (1987) as part of the basic 1:100.000 geological map. According to Šifrer (1965) the distribution of till and proglacial deposits suggests that the Soča Glacier was divided into two ice lobes south of Tolmin. Although glacial landforms and deposits in this area have been identified and described very precisely, it is unclear whether they were deposited over the course of one or several glaciations. Any reliable absolute dating that could reveal the age of glacial deposits around Most na Soči is still missing.

This study focuses on late Quaternary deposits in the Modrejce Valley located between Tolmin and Most na Soči (Fig. 2), where steep cliffs provide good exposures for the study of stratigraphic relationships among the sedimentary units.

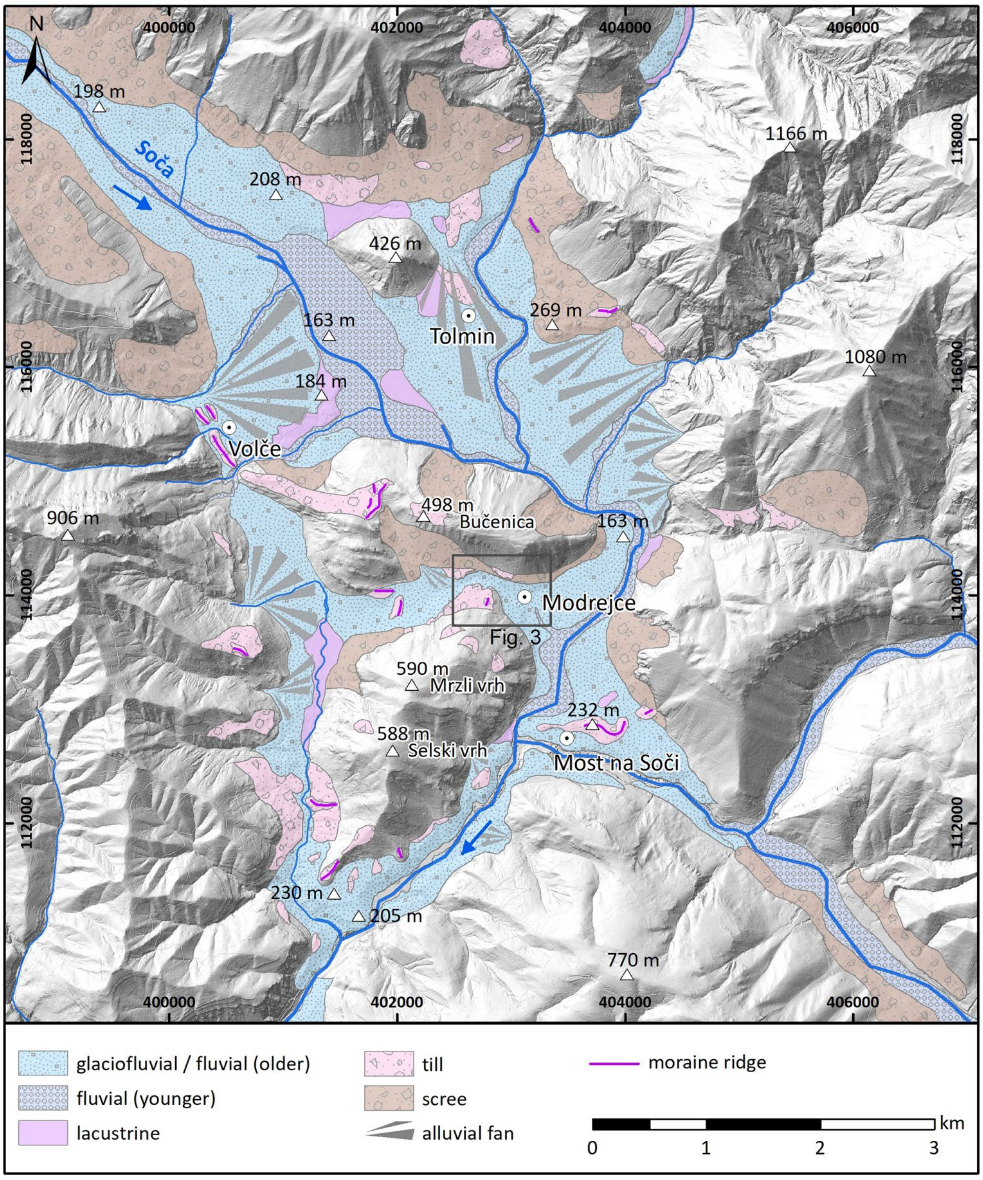

Fig. 2. Distribution of Quaternary deposits in the Tolmin and Most na Soči areas (updated after Šifrer, 1965 and Buser 1987). Shaded relief is derived from LiDAR based DEM (Ministry of the Environment and Spatial Planning, Slovenian Environment Agency, 2011).

Using geological and geomorphological mapping and sedimentological analysis we investigated the landforms and deposits, interpreted their sedimentary environments, and established their relative chronological relationships. This enabled us to reconstruct the late Quaternary sedimentary evolution of this area in relationship to glacial advances and slope dynamics.

Methods

Quaternary landforms and deposits in the Modrejce Valley were studied using geomorphological and geological mapping, as well as sedimentological facies analysis. A map of Quaternary deposits in the wider Tolmin area (Fig. 2) was summarized from Šifrer (1965), Buser (1987) and our GIS- and field-based geomorphological and geological mapping. A detailed map of Quaternary landforms in the selected area of Modrejce (Fig. 3A) was prepared by means of field-based geomorphological and geological mapping along with a stacked cross-section (Fig. 3B) and description of landforms (Figs. 4 and 5) and deposits (Fig. 6).

Geomorphological mapping was based on LiDAR data with a relative horizontal and vertical accuracy of 0.30 and 0.15 m, respectively (Ministry of the Environment and Spatial Planning, Slovenian Environment Agency, 2011). The LiDAR-based DEM with 1 m resolution was used to generate a shaded relief map, a slope degree map, a slope aspect map and contour lines with an equidistance of 1 m. These various topographic representations helped to distinguish different geomorphic characteristics associated with Quaternary sedimentation and erosion (e.g. terraces, cliffs, moraines, colluvial fans).

Quaternary deposits were documented using field sedimentological logging. Each unit was described according to its lithology using classifications by Wenthworth (1922) and Folk et al. (1970) and according to its various sedimentary characteristics described by Tucker (2011). The lithology of the units is described based on macroscopic observations. The lithological composition of the clasts is given qualitatively. Facies are summarized according to Eyles et al. (1983) and Miall (2006) codes respectively for glacigenic and alluvial/deltaic deposits (Table 1) and into facies associations as in Miall (2006) and Benn and Evans (2010). This approach enabled us to gather the data necessary to interpret the depositional environment, its evolution and clast provenance.

Quaternary deposits in the Soča Valley around Tolmin and Most na Soči

The Soča Valley floor around Tolmin and Most na Soči is mainly covered with glaciofluvial, fluvial and alluvial fan deposits (Fig. 2). Two units of fluvial deposits were distinguished: the younger fluvial deposits represent the Holocene thalweg of the Soča River, and the older fluvial and glaciofluvial deposits are terraced. The terraces have risers that vary in size from several meters to more than 50 meters. In several places the terraces are covered by alluvial fans related to small tributaries of the Soča River. Based on relative elevation, landform preservation, sediment characteristics, pedogenesis and cementation, the terraces are assumed to be Middle to Late Pleistocene in age, while the alluvial fans are assumed to be Late Pleistocene (Šifrer, 1965).

Lacustrine and glacial sediments are also present in the valley, whereas scree deposits are

Table 1. Facies codes used in this study are summarized from Eyles et al. (1983) and Miall (2006).

Facies code	Facies	Sedimentary structures
Gcm	Clast-supported, massive gravel	/
Gmm	Matrix-supported, massive gravel	Weak grading
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication
Gp	Gravel, stratified	Planar cross-beds
Gt	Gravel, stratified	Trough cross-beds
Sm	Sand, fine to coarse	Massive, or faint lamination
Sh	Sand, very fine to coarse, may be pebbly	Horizontal lamination
Sr	Sand, very fine to coarse	Ripple cross-lamination
Fl	Sand, silt, mud	Fine lamination, very small ripples
Fsm	Silt, mud	Massive
Dmm	Matrix-supported, massive diamict	/
Dms	Matrix-supported, stratified diamict	Stratification more than 10 % of unit thickness
Dcm	Clast-supported, massive diamict	/
Dcs	Clast-supported, stratified diamict	Stratification more than 10 % of unit thickness
Dcg	Clast-supported, graded diamict	Vertical grading in clast content

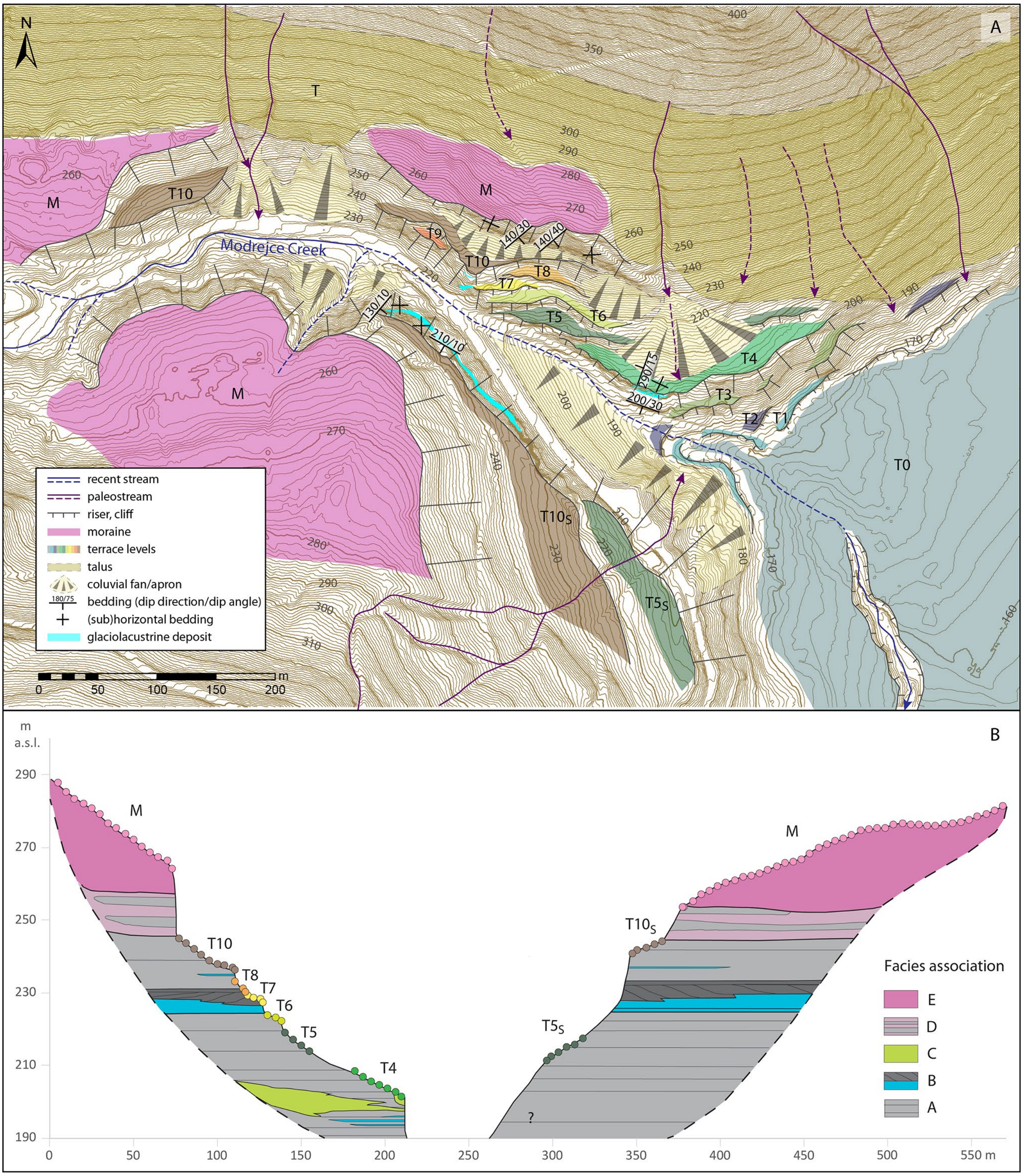

Fig. 3. Quaternary landforms and deposits of the Modrejce Valley. A - Geomorphic map. B – Stacked cross-section of landforms and facies associations. Note that in order to capture all units, the topographic profiles of individual landforms were projected into stacked cross-sections from different parts of the map. The points at the surface are the actual projected vertices taken from the LiDAR DEM every 5 m across the terrace-like landforms. Topographic contours 1 m equidistant from each other are derived from LiDAR based DEM (Ministry of the Environment and Spatial Planning, Slovenian Environment Agency, 2011).

abundant on the toe of valley slopes. Lacustrine sediments are laminated and well-consolidated muds, silts to sands. Their stratigraphic relation to the glaciofluvial succession places their deposition into glaciation (Šifrer, 1965). Glacial deposits are spread on the saddle that closes the Modrejce Valley to the west (Fig. 2) up to about 280 m a.s.l. and form morainic ridges, whose outcrops show loose glacial deposits. Here, a thin soil (about 10 cm) developed on them and the deposit lacks any considerable sign of weathering. The shape of these moraines indicates they are well preserved, and their minimal weathering is similar to that of the LGM glacial deposits in the nearby area (Monegato et al., 2007; Žebre et al., 2013; Colucci et al., 2014), suggesting a comparable young age. Cemented and weathered glacial deposits are also present within the succession and at different elevations up to about 500 m a.s.l.; they were likely deposited in different phases of glacial advance during the LGM or earlier (Šifrer, 1965).

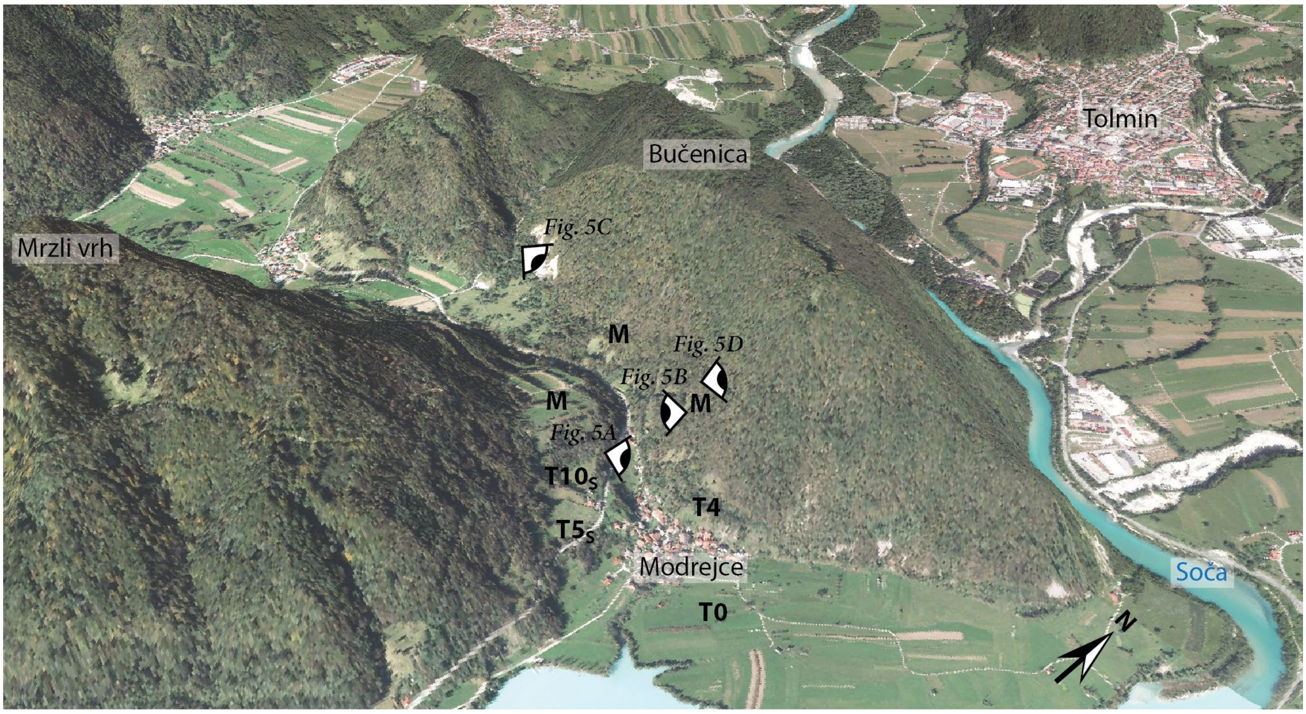

Fig. 4. Three-dimensional view of the Modrejce Valley with main landforms from the Fig. 3 (M – moraine, T4, T5S and T10S – terraces) and locations of the photos from Fig. 5. Digital orthophoto (Public Information of Slovenia, the Surveying and Mapping Authority of the Republic of Slovenia, DOF, 2011) is draped over LiDAR-based DEM (Ministry of the Environment and Spatial Planning, Slovenian Environment Agency, 2011).

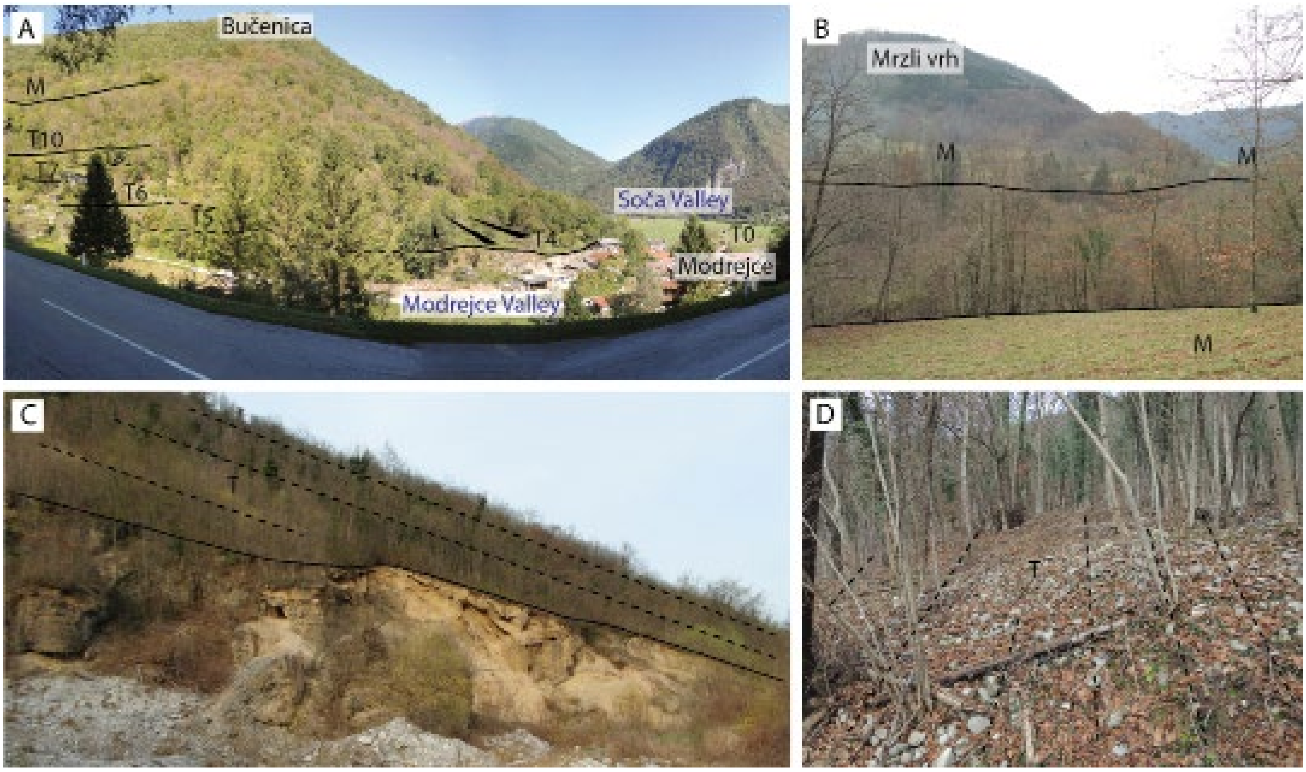

Fig. 5. Field photos of the Modrejce Valley landforms. A – Moraine, terraces and colluvial fan on the NE slopes of the valley. B – Moraines on both sides of the valley (photo taken from the NE side). C – Talus slope with corresponding scree deposits outcropping in a quarry on the NE slopes. D – Talus slopes above the moraine on the NE side. See Fig. 4 for locations of the photos.

Quaternary deposits and landforms of the Modrejce Valley

The Modrejce Valley is a tributary valley of the Soča Valley, running between the Bučenica and Mrzli vrh hills northwest of Most na Soči (Fig. 2). The Modrejce Creek runs through the valley. The bedrock on the NE slopes consists of platy Volče limestone with chert (Upper Cretaceous; Coniacian – Campanian), which is separated by the dextral strike-slip Idrija Fault from the coarse-grained limestone breccia with intercalations of flysch (Upper Cretaceous; Maastrichtian) building the bedrock on the SW slopes (Buser, 1987). The valley hosts glacial sediments, as well as glaciofluvial and scree deposits (Šifrer, 1965).

Ten terrace-like surfaces separated by steps and cliffs were mapped on the hillslopes of the Modrejce and Soča valleys between 170 and 250 m a.s.l. (Figs. 3 and 5A). These surfaces are tens of meters wide and are not flat like common terraces; they instead slope gradually (5–15°) towards the valley bottom, in contrast to the steep slope of the valley flanks. The related deposits are partially covered by colluvial fans and aprons. Moraines are present at higher elevations (250–280 m a.s.l.) and characterize the saddle closing the Modrejce Valley to the west (Figs. 3 and 4). Talus is present at even higher elevations (Figs. 3A and 5C, D).

The cliffs expose a complex series of Quaternary clastic deposits of mostly sandy conglomerates to gravels (Gh, Gp, Gt, Gcm) intercalated with layers of sandstones, sands (Sm, Sh, Sr) and silts (Fl, Fsm) (Fig. 6A-I). Local clast-supported to matrix-supported coarse breccias (Dcs, Dcm, Dcg) are interbedded. Matrix-supported diamicton (Dmm, Dms) characterizes some thick layers. The prevailing lithology of the clasts is limestone, whereas other lithologies occur including chert, cherty limestone, red marly limestone (Scaglia Rossa Formation), sandstone with mica, green marl and dolostone. Layers are mostly sub-horizontal; in some outcrops the bedding gently dips SE, WNW or SWS. Cross-bedding dips W to SW, indicating the transport from E and NE.

The mapped deposits in the Modrejce Valley can be divided into five facies associations (FA) (Fig. 3B) according to their lithologic properties and their stratigraphic relations.

The FA-A consists of horizontal- to cross-bedded sandy gravels (Gh, Gp) with beds of crudely bedded gravels (Gcm) (Fig. 6A-B). Clast-size ranges from fine grained pebble to cobble and even small boulders occur. Gravels are poorly sorted and clast-supported; they are mostly cemented but with some loose gravel layers. Clasts are sub-angular to rounded, mostly sub-rounded clasts prevail, some layers of prevailing rounded or sub-angular clasts occur. Lenses of massive silt and sand (Fsm, Sm) are interbedded.

The FA-A can be associated with fluvial deposition. The sedimentary structure with horizontal- and cross-bedding is typical for braided river deposits (Miall, 2006); however, the variation in roundness between subangular and rounded clasts stands in contrast to the fluvial environment typical of the Soča River during a warm period. The Soča River flows along its valley for about 60 km before reaching the investigated location, and its Holocene gravels are well rounded. Cross bedding in outcrops below T10 and T4 indicates the sediments were mostly deposited from E, NE and SE, which points to the Soča Valley. Also, the lithological composition of clasts indicates paleo-Soča provenance. Local sedimentation by the Modrejce Creek is therefore excluded. Based on the roundness of the clasts and the largely poorly sorting we interpret the FA-A as glaciofluvial, related to the outwash stream of the Soča Glacier close to the valley slope.

FA-B is represented by a coarsening upward succession from laminated or massive silt (Fl, Fsm) to cross-bedded conglomerates (Gp), outcropping on both sides of the Modrejce Valley (Fig. 3B). Thick lenses of horizontal- and cross-laminated sands (Sh, Sr) and silts (Fl) with angular to sub-rounded dropstones up to 10 cm in size (Fig. 6D) occur below T4. Sand ripples (Sr) are visible in some parts of these layers. A succession consisting of horizontal-laminated silt to sand (Fl, Sh) up to 2 m thick crops out in the cliff below T10 on both sides of the Modrejce Valley (Fig. 6E-G). There, silts and sands occasionally include sub-angular to rounded dropstones up to 2 cm in size. Laminas of sandstone with sand ripples (Sr) are locally present within loose sand. The succession shows reverse gradation from silts at the bottom to fine and coarse sands towards the top. Although not continuously exposed, the lateral extent of this succession can be followed in the southern cliff for some 150 m. The fine-grained succession is overlain with fine grained conglomerates (Gp, Gh), followed by coarser grained conglomerates (Gp, Gh), with angular to sub-rounded clasts. The cross-bedding dips about 30° to the SW (Fig. 6H).

The finer layers of laminated silt and sand with dropstones and sand ripples (FA-B) intercalated within the FA-A are interpreted as lacustrine toesets and bottomsets. Since they occur within the glaciofluvial succession and include dropstones they are likely related to a glaciolacustrine environment. Moreover, the thicker succession of reverse grading silts and sands in the cliff below T10S followed first by cross-bedded sandy conglomerates dipping towards the SW and then horizontal- to cross-bedded sandy conglomerates likely indicate toeset to foreset transition in a Gilbert-type delta succession (e.g. Nemec, 1990) at the margin of the glacier in a southwestward progradation during glacial advance.

FA-C consists of layers of sandy breccia (Dcs, Dcm) occasionally present as interbedded layers within sandy conglomerates of FA-A. The sandy breccia is poorly sorted and clast supported, with angular to sub-rounded clasts, where sub-angular clasts prevail (Fig. 6C). In one case, we found facies of boulder size breccia without matrix (Dcg), filling the depression in FA-A in a cliff below T4. This breccia is massive, clast-supported, cemented and normally graded (Fig. 6J). The

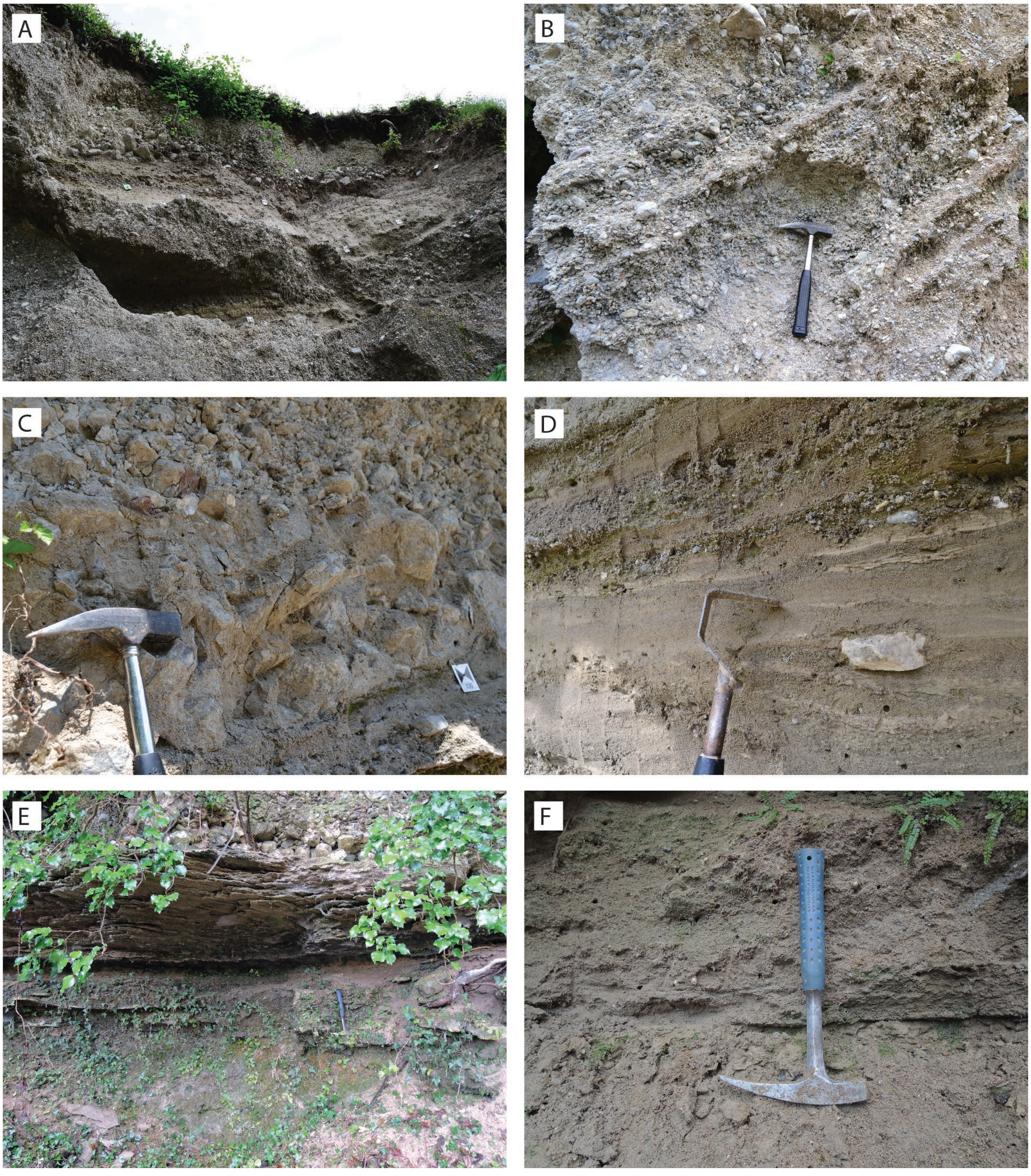

Fig. 6.

clasts are angular to rounded, while sub-angular clasts prevail. Clasts range in size from 10 cm to more than 1 m.

Layers of sandy breccia may be interpreted either as facies of glaciofluvial deposits or as slope deposit. In some cases, the dipping of layers towards S (towards the bottom of the valley) suggests deposition from the slopes. Facies of boulder-size breccia without matrix (Dcg) is peculiar in the system in view of the large size of the clasts and the absence of matrix. Due to the normal grading and roundness of the clasts we assume these deposits were formed by slope redeposition. The slope material likely originated from older glacial or periglacial sediment higher on the slopes, since some clasts within this FA are sub-rounded. Therefore, short gravity slope material was likely mixing with glaciofluvial material.

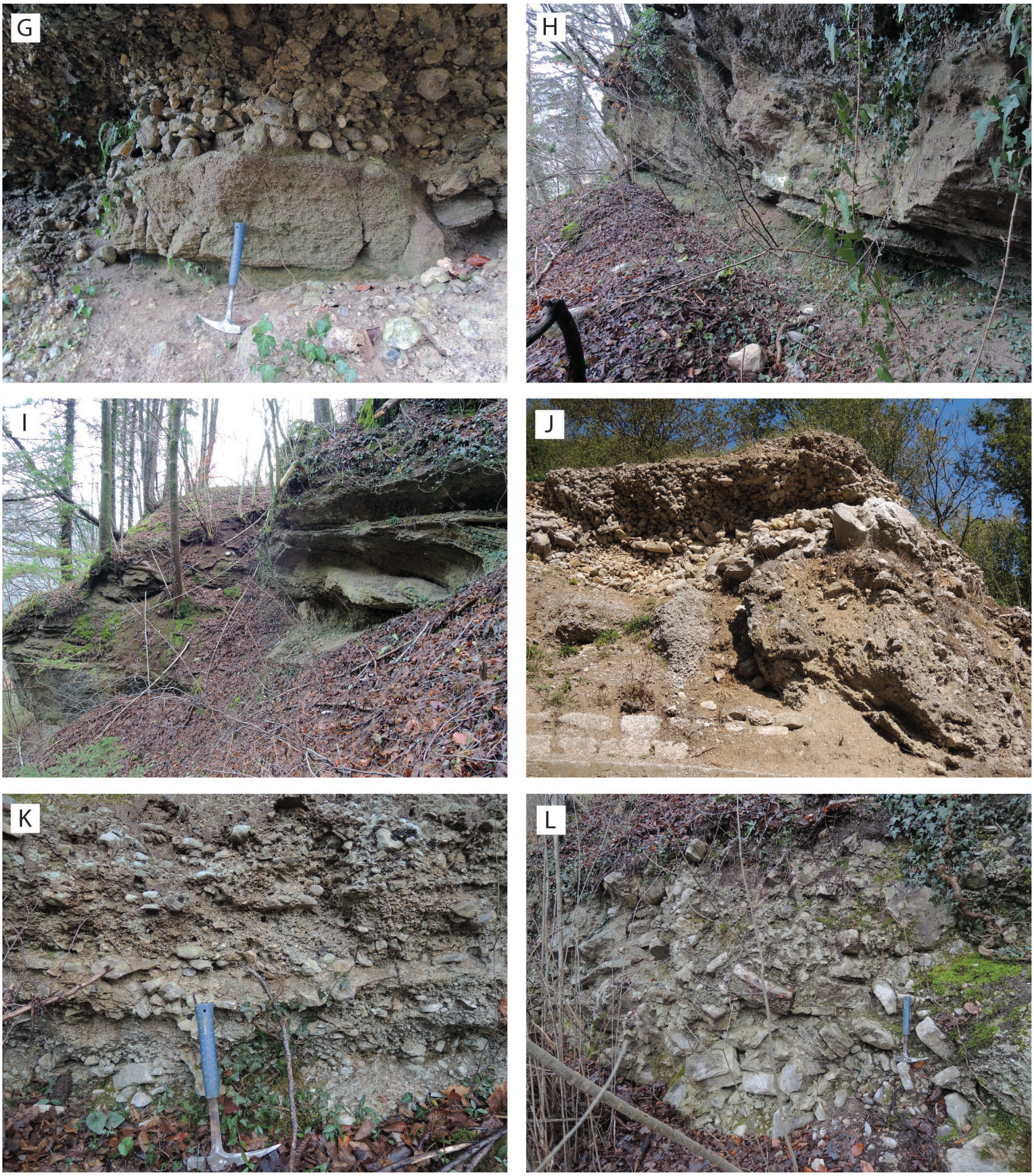

Fig. 6.

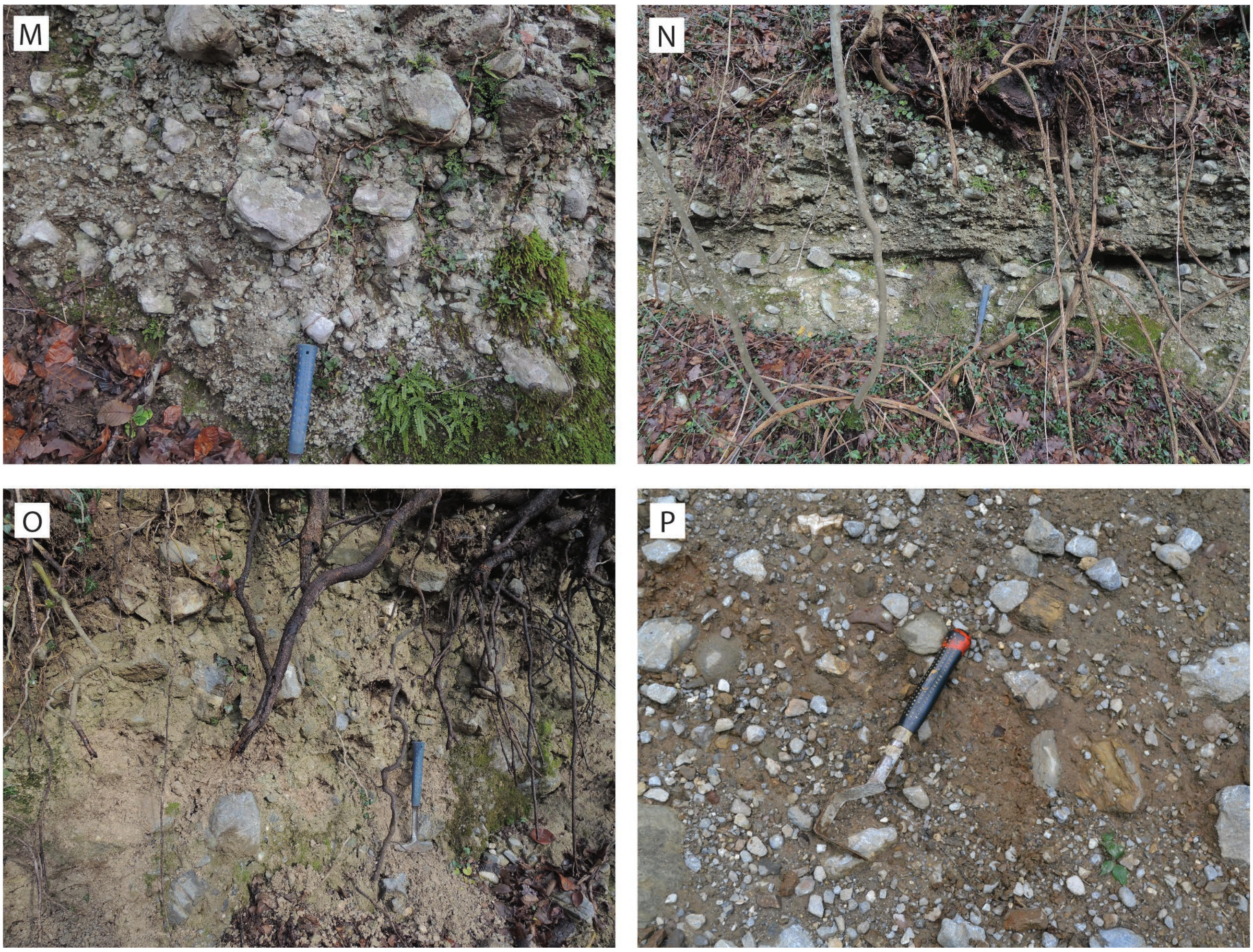

Fig. 6. Outcrops visible on the cliffs of the Modrejce Valley (A-D and J: cliff below terrace T4; E-I: cliff below terrace T10S; K-O: cliff below moraine; P: top of moraine). A – Silt and sand (Fsm, Sm) interbedded with cemented sandy gravel (Gcm, Gh). B – Sandy conglomerate with cross-bedded structure (Gp). C – Sandy breccia (Dcm). D – Horizontally laminated silt to sand with dropstones (Fl, Sh). E – Horizontally laminated silt (Fl) to sand (Sh, Sr) overlaid with sandy conglomerate (Gcm). F – Sand with scattered pebbles (Sm). G – Laminated sandstone (Sh) overlaid with sandy conglomerate (Gh). H - Horizontally laminated sand (Sh) overlaid with cross-bedded sandy conglomerate (Gp). I – Vertical coarse grading of horizontal- and cross--bedded sandy conglomerate (Gh, Gp). J – Boulders without matrix filling the depression over sandy conglomerate (Dcg). K – Horizontally-bedded coarse sandy gravels (Gh). L – Massive sandy breccia with chaotically oriented angular clasts (Dcm). M – Massive sandy conglomerate (Gcm). N – Contact between sandy breccia below (Dms) and sandy conglomerate (Gh) on top. O and P – Matrix supported, massive diamicton (Dmm).

FA-D is a complex association consisting of prevailing sandy breccia (Dcm, Dcs, Dmm, Dms) interbedded with sandy conglomerates (Gh, Gcm). Alternating stratified (prevailing; Dcs, Dms, Gh) and massive facies (Dmm, Dcm, Gmm, Gcm) occur and clast-supported (prevailing; Dcm, Dcs, Gcm, Gh) and matrix-supported facies (Dmm, Dms, Gmm) are present (Fig. 6K-N). Sandy breccia is poorly sorted, clast supported, with angular to rounded clasts, where angular to sub-angular clasts prevail. In parts, it consists of horizontally-bedded sandy breccia with fine-grained horizons (average clast size 2–8 mm, maximum 1 cm) and coarse-grained ones (average clast size 2 cm, maximum 15 cm) (Fig. 6K). In other parts, the sandy breccia is massive (Dcm), clast supported, with fine grained gravel and sand as a matrix and chaotically oriented angular clasts of up to 50 cm in size (Fig. 6L). Boulders more than 1 m occur locally within the breccia. Occasionally, the breccia is replaced by massive to stratified, poorly sorted and clast supported sandy conglomerates (Gh, Gcm), with angular to rounded clasts, with sub-rounded clasts prevailing (Fig. 6M). Interbedding between prevailing stratified and less often massive structure, clast- and matrix-supported structure, breccia and conglomerates, continues through this part of the Modrejce succession. The prevailing lithology of the clasts is limestone, whereas marls and limestone with chert are also common, and other lesser lithologies include red marly limestone (Scaglia Rossa Formation), sandstone with mica, green marl and dolostone. Layers are mostly sub-horizontal, with occasional SE dipping layers also outcropping. The deposits of this FA are cemented, and clasts, which are composed of clastic rocks partially weathered in otherwise not pedogenized deposits.

The mixing association FA-D crops out in the cliff below the moraines and indicates a continuous change in the depositional mechanism from glacial (massive, matrix-supported sandy breccia to conglomerate with chaotically oriented clasts) to glaciofluvial (stratified, clast supported, poorly sorted conglomerates), where the glaciofluvial may be related to the proglacial or subglacial streams.

FA-E consists of facies of massive and matrix-supported silty to sandy diamicton (Dmm) with boulders (Fig. 6O), with local lenses of massive sand (Sm) and gravels (Gmm). This diamicton has angular to rounded clasts, some of which are striated and polished. The deposit is normally- to over-consolidated towards the bottom. Clasts have not developed weathering rings, and deep weathering structures are absent, with only a thin layer of soil (roughly 10 cm) developed on these deposits.

The FA-E characterizes the uppermost deposits, which are interpreted as a glacial till and are morphologically represented by lateral moraines present at 250–280 m a.s.l. in the Modrejce Valley; these belonged to the sedimentation by the two lobes of the Soča Glacier surrounding Mount Bučenica (Fig. 2).

Our interpretations of the depositional environments of FA-A, FA-B, FA-D and FA-E are consistent with earlier interpretations by Šifrer (1965). At several points in the Soča Valley, between Tolmin and Most na Soči, Šifrer also noted that certain terraces include sediments with different genesis and that these sediments do not correspond to the individual terrace as a landform, since the terrace landforms are cut into older sediments. Likewise, geomorphological evidence indicates that terrace-like surfaces T4-T10 in the Modrejce Valley are not related to glaciofluvial deposits exposed in the cliffs. The studied glaciofluvial succession was deposited from the bottom of the valley upwards, regardless of the terrace levels, as suggested by a glaciolacustrine layer 2 m thick outcropping in the cliff below T10S on the southern side, and below T7 on the northern side of the valley. In contrast, fill terraces would each be composed of material of the same sedimentary facies origin and the uppermost terraces would include the older deposits. This suggests that the terrace-like surfaces T4-T10 in Modrejce are likely erosional landforms.

Since glaciofluvial deposits were overrun by the glacier, terrace-like landforms were probably cut into glaciofluvial and glaciolacustrine deposits by subglacial erosion and mostly by subsequent post-glacial fluvial erosion, additionally reshaped by ongoing slope processes. Any sediments related to glacial and post-glacial fluvial erosion processes were not preserved in the exposed cliffs below terrace-like surfaces, except for the glacial deposits in the uppermost flat area (FA-E). However, they could be present on top of the terrace-like surfaces, but due to the lack of outcrops there, this cannot be verified without invasive research techniques. Furthermore, any sediments from this period would be buried near the slopes by the younger colluvial fans and aprons visible in the geomorphology (Fig. 3). Based on the geomorphological evidence alone, it could be speculated that post-glacial erosion may have created two paired and eight unpaired terrace-like surfaces. Their relationships are not clear due to the complex depositional and erosional history of the valley. The erosional processes were likely partly impacted by the lithological changes between glaciolacustrine and glaciofluvial deposits, promoting steep slopes in coarse-grained cemented units.

The lowermost terraces T0-T3 were not subjected to detailed sediment mapping. Based on spatial distribution, T1-T3 landforms are more likely fluvial terraces. T0 is one of a few broader Soča terraces (Šifrer, 1965).

Evolution of Quaternary sedimentary environment in the Modrejce Valley

The stratigraphic architecture of the Modrejce Valley deposits suggests that several phases of deposition and erosion occurred during the late Quaternary. The glaciofluvial environment (FA-A) related to the Soča Glacier was occasionally mixing with short-period (glacio)lacustrine (FA-B) and the slope deposition environment (FA-C). Towards the top of this succession, the glaciolacustrine delta deposits (FA-B) indicate the close proximity of the glacier. The succession continues with the glacial deposition in exchange with the glaciofluvial one (FA-D). The overall succession was buried by glacial deposits (FA-E). The subsequent incision of the Modrejce Valley was characterized by slope deposition, which continues to this day. The entire studied succession, except for the covering slope deposits, was therefore deposited during cold phases and recorded fluctuations in the glacier terminus position around Tolmin and Most na Soči. Phases of glacial advance and

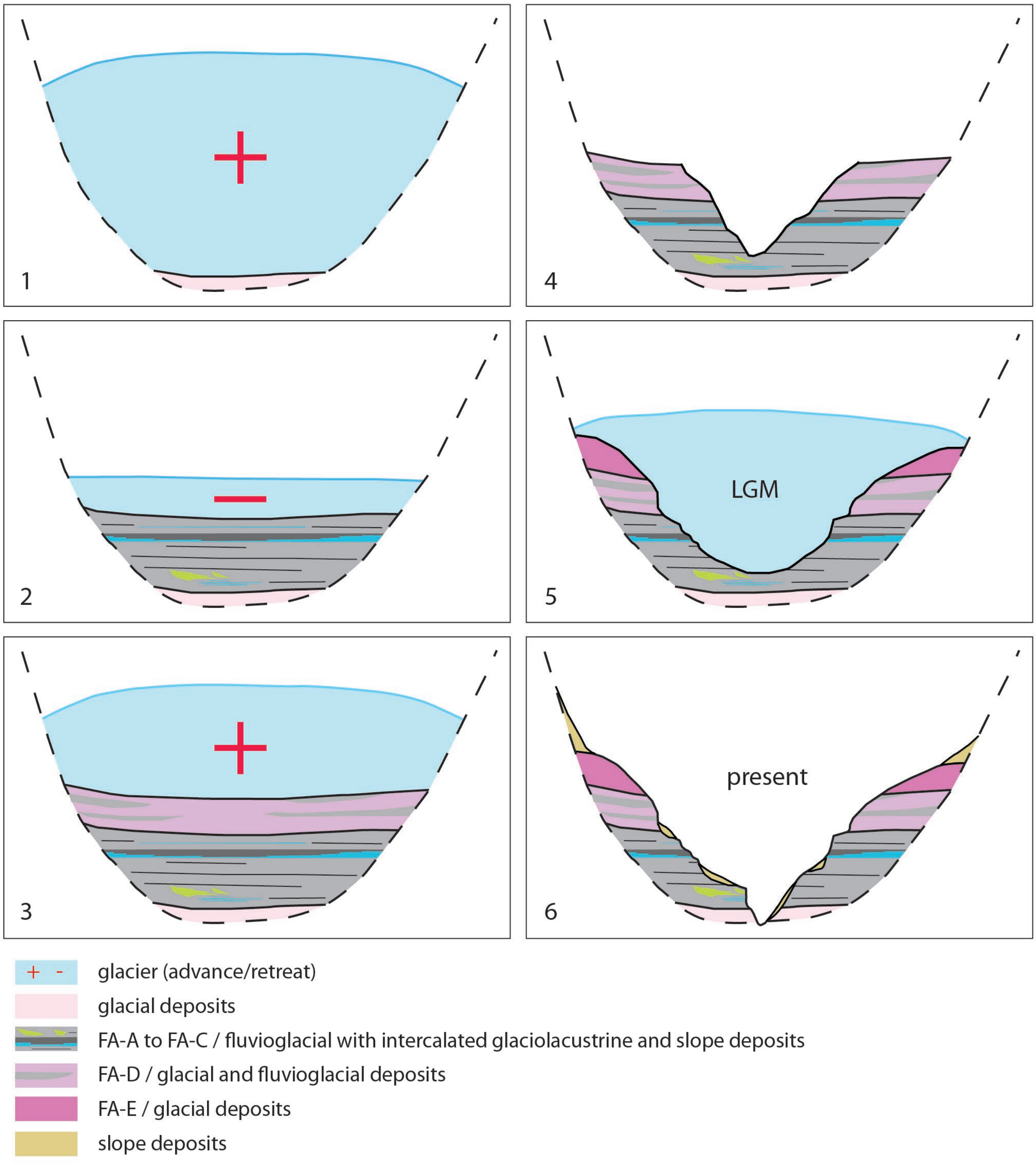

Fig. 7. Reconstruction of sedimentary phases showing the unique situation in the Modrejce Valley.

retreat were already proposed in this area by Šifrer (1965), based on geomorphic and sedimentological records in the Soča Valley (Fig. 2).

The sedimentological and geomorphic records presented in this study show that the succession was likely deposited over the course of at least two different glacial phases (Fig. 7). In the later glacial phase, FA-E was deposited. Its degree of weathering (shallow soil, absence of deep weathering structures such as deep soil or cryoturbation and no weathering rings on clasts), the absence of cementation and the preservation of landforms (moraines present, with no erosion features developed on their surfaces) in the Modrejce saddle point to the LGM age. Similar type of landforms that have been clearly attributed to the LGM remain preserved in the south-eastern Alpine valleys (e.g., Pellegrini et al., 2005; Ravazzi et al., 2012; Colucci et al., 2014). One of the modeled extents of the LGM glaciation by Seguinot et al. (2018) also nearly reached Tolmin and is thus roughly in agreement with our estimation. In an earlier glacial phase, FA-A to FA-C were deposited during the glacier retreat phase and FA-D deposited during the following glacier advance into the Modrejce Valley. In view of the overall cementation of FA-A to FA-D, the presence of partly weathered clasts of clastic rocks in otherwise not pedogenized glacial diamicton (Dmm) in FA-D and the absence of related landforms it is likely that deposition of these successions occurred before the LGM and that successions were subsequently covered by lodgment till deposits (e.g., Reitner and Draxler, 2002). The succession of FA-A to FA-D was then eroded during the subsequent interglacial/interstadial phase and carved by the Soča Glacier during the last glacial advance, when moraines (FA-E) were settled all along the flat areas of the Modrejce Valley. During the Late Glacial, the succession was eroded again as a result of post-glacial processes; small flat surfaces were shaped into a staircase-like slope. During the Holocene, a final slope/scree deposition was established and continues to this day.

Similar slope developments as in Modrejce Valley can be observed in post-glacial incisions in Alpine valleys (e.g. Ravazzi et al., 2012; Reitner et al., 2016). However, it is a rare case that older deposits have been preserved in such abundance after the interglacial / interstadial erosion phase and the subsequent glacial accumulation and erosion phase. The conservation capacity of older loose and poorly cemented sediments during glacial erosion is negligible, everywhere in similar environments in the Alpine region. The exceptional case in our study could be due to the sheltered position of Modrejce Valley in the passage between the hills Bučenica and Mrzli vrh, which was located outside the two main erosion corridors of the Soča Glacier, which split and encased around Bučenica (Fig. 2). Our interpretation of the depositional records thus represents a new and original contribution to the understanding of glacial and post-glacial landscape development.

Our reconstruction implies that the last, as well as one of the earlier glaciations reached the Most na Soči area, as suggested by Šifrer (1964/1965) and even earlier studies (Brückner, 1891; Tellini, 1898; Penck & Brückner, 1901–1909; Feruglio, 1925; Winkler, 1931; Melik, 1954). Since our provisional age estimates are based on comparisons of qualitative data, further quantitative chronological indications are needed to better narrow and constrain the age of these glacial advances, which information would cast new light on the geomorphological evolution of the Most na Soči valley knot.

Conclusions

Our study of the Quaternary deposits in the Modrejce Valley offers new insights into the extent of glaciation in the Slovenian Alps, especially in the Soča Valley. The Quaternary sedimentary environment in this area developed in response to glacial dynamics from glaciofluvial, glaciolacustrine and slope intercalation to glacial deposition. Depositional records of glaciofluvial, glaciolacustrine and glacial sedimentation in the Modrejce Valley are related to the Soča Glacier and show that the glacier reached the Most na Soči area twice in the late Quaternary. The investigated succession was deposited over the course of two different glacial periods, which we interpreted as LGM and pre-LGM glaciation. The glacial and glaciofluvial deposits from the earlier phase are abundant, despite the subsequent glacial overflow in the LGM. This is probably due to the unique sheltered position of Modrejce Valley, which was outside the main erosional path of the Soča Glacier. Such sites are of crucial importance for the study of alpine glacial history. Further work with absolute dating methods is necessary to narrow the age of these glacial advances.

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