Sedimentological and geomorphological characteristics of Quaternary deposits in the Planica-Tamar Valley in the Julian Alps (NW Slovenia)

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ABSTRACT
We present a geomorphological map on a scale of 1:15,000, with detailed sedimentological descriptions, and a general relative spatio-temporal depositional reconstruction of Quaternary sediments in the Planica-Tamar Valley (NW Slovenia). After the Last Glacial Maximum, the retreating Quaternary glacier deposited large amounts of glacial sediments. These were followed by Holocene sediments, which differ in their sedimentological characteristics, transport mechanisms, and morphology. These sediments are deposited as sedimentary bodies with complex depositional geometries. They form areas of active, partly active, and inactive sedimentation in response to local/regional climate and bedrock geology. Previous research of the valley was mainly focused on bedrock mapping, while almost completely neglecting Quaternary deposits. This work is the first broader analysis of Quaternary sedimentary deposits in the research area, which offers an insight into the complex geomorphological and sedimentological processes, which shape the current mountainous landscape.

1. Introduction
The research area of the Planica-Tamar Valley in NW Slovenia (Figure 1(a)) is orientated in an N–S direction with an elevation range between 850 and 1300 m above sea level (a.s.l.). The Planica Valley begins close to the village of Rateče (Figure 1(b)) at approximately 850 m a.s.l. and is best known for the Planica Nordic Centre. At 1100 m a.s.l., close to the Tamar hut, the Planica Valley transits to the Tamar Valley, which ends under the slopes of the Jalovec Mountain. For the purpose of this study, we refer to both valleys as the Pla-nica-Tamar Valley. The valley has a climate typical of low mountain regions, with high annual precipitation (1531 mm of rainfall) and low annual temperature (ranging from 4.6°C to 8°C; cf. Kajfež-Bogataj, 1996; Slovenian Environment Agency [ARSO], 2006; cf. Fidej et al., 2015). There are no permanent streams, only torrential ones, which have an abrupt discharge increase during heavy precipitation events.

The valley is glacially U-shaped, with steep upper slopes composed of Upper Triassic, mainly carbonate bedrock, which was the main focus of geological mapping and research in the past decades (Celarc, 2004; Celarc & Placer, 2006; Celarc, Gale, & Kolar-Jurkovšek, 2013; Gale et al., 2015; Jurkovšek, 1987a, 1987b; Ogorelec et al., 1984; Ramovš, 1981). The bedrock succession starts with Julian Conzen Dolomite (in the northern and central parts of the valley), followed by Tuvalian to Norian Tor Fm., Portella Dolomite, Carnitza, Fm., Bača Dolomite Fm., Fraunkogel Fm., and ending with Norian to Rhaetian Dachstein Limestone, located in the southern part of the valley (Gale et al., 2015).

The lower valley slopes and floor are covered by Quaternary sedimentary deposits, which have received less attention in the past (Bohinec, 1935; Popit, Ver-bovšek, Rožič, & Šmuc, 2013; Šmuc, Janecka, Lempa, & Kaczka, 2015; Zupan, 2013). The more gently inclined lower slopes consist of several fan-shaped Holocene deposits (Popit et al., 2013) that onlap onto the relatively flat to undulated valley floor deposits marked by Pleistocene glacial and lacustrine deposits (Bohinec, 1935; Triglav Čekada, Barborič, Zorn, & Ferk et al., 2015). The Quaternary deposits are forming large, complex, and intercalated sedimentary bodies with their distinct morphology, sedimentological structures, and transport and depositional mechanisms. The well-pronounced outcrops offer a unique opportunity to study the evolution of the landscape after glacier retreat following the Last Glacial Maximum.

The aims of this study are (i) to present a detailed geomorphological map of Quaternary sedimentary deposits in the Planica-Tamar Valley, (ii) to determine their sedimentary deposition activity, (iii) to describe sedimentological and morphological characteristics of different mapped sedimentary deposits and identify the main sediment transport mechanisms, and (iv) to...
Figure 1. (a) Location of the research area in Slovenia marked by a red rectangle which is presented in (b). (b) Area of the Main Map of the Planica-Tamar Valley marked by a red rectangle (DEM source: ARSO, 2015; Tarquini et al., 2007; Tarquini et al., 2012; Tarquini & Nannipieri, 2017).
tentatively reconstruct a general relative spatio-temporal sediment deposition.

This paper represents one of the first studies in Slovenia, combining geomorphology, sedimentological description, and mode of transport to define individual mapped units and relate them to climate and bedrock geology in a mountain environment. Additionally, this work provides information and basis for slope mass movement and natural hazard risk assessment.

2. Materials and methods

2.1. Mapping and data source

The presented map is a result of field geomorphological mapping and shaded digital terrain model (DTM) analysis. Geomorphological mapping methods and organisation of the map follow the works and studies of Smith, Paron, and Griffiths (2011) and Piacentini, Urbano, Sciarra, Schipani, and Miccadei (2015). During fieldwork a 1:5000 topographic map (The Surveying and Mapping Authority of the Republic of Slovenia – GURS, 1967, 1986) was used as a base map. Quaternary sedimentary deposits were defined and mapped in the field based on their sedimentological characteristics, morphology, and prevailing transport mechanism. Based on these criteria, six different types of sedimentary deposits forming several individual sedimentary bodies were identified and accurately mapped, each one marked with its own colour. These deposits are thoroughly described in Section 3. In case of the alluvial fan deposits, areas of active (recent), partly active, and inactive sedimentation were mapped. We consider the most recent deposits as areas where sediment is currently actively transported and deposited, and where clasts show little or no surface weathering. Areas of sediment deposits, covered by lichens, grasses, or shrubs, where clasts show surface weathering, but no developed soil, were marked as partly active areas. Areas covered by vegetation and developed soil were marked as inactive areas. Talus slopes were only defined as active (recent deposition) and inactive (talus slopes covered by vegetation and developed soil). Prominent morphological features such as V-shaped ravines, approximate depths of channel scarps (deeper or shallower than five metres), topographic ridges, active or inactive torrential channels, and areas of anthropogenically reworked deposits are mapped on individual sedimentary bodies. Sedimentary process of sedimentary flow direction is mapped, along with other features such as cross-section location, and boundaries and assumed boundaries of individual sedimentary bodies. Due to vegetation and complex depositional geometry of the sedimentary bodies, boundaries between them were sometimes difficult to determine in the field. In those cases, boundaries were mapped based on the shape of the sedimentary body or terrain roughness from the shaded DTM, which also presents the Main Maps basis. Shaded DTM is based on lidar scanning, performed by the Geodetic Institute of Slovenia (2015a, 2015b) with a resolution of 1 × 1 m (available http://gis.arso.gov.si/evode/profile.aspx?id=atlas_voda@Arso; ARSO, 2015). Nevertheless, some boundaries between individual sedimentary bodies could not be accurately determined and are therefore marked as assumed boundaries.

2.2. Software and map design

The geomorphological map was designed in QGIS (2014, https://www.qgis.org/en/site/) and the final map adjustments were made in Adobe Illustrator. Based on the geomorphological map, fieldwork examination, and the DTM, a W–E orientated cross-section over the valley was made. A topographic profile was extruded from the DTM using the ‘Terrain profile’ plugin in QGIS. The topographic profile was exported to Adobe Illustrator where pre-Quaternary bedrock and different sedimentary deposits were marked depending on their location on the map. The cross-section is used for a preliminary relative spatio-temporal depositional reconstruction of Quaternary sediments and a tentative presentation of the complex depositional geometry of the sedimentary bodies.

3. Overview of the geomorphological map

3.1. Characteristics of Quaternary sedimentary deposits in the Planica-Tamar Valley

Based on sedimentological and morphological characteristics six different types of sedimentary deposits were defined. These are glacial deposits, lacustrine deposits, fluvial deposits, alluvial fan deposits, a debris flow deposit, and talus slope deposits (Main Map). The sedimentological and morphological characteristics of each sedimentary deposit type along with their prevailing sediment transport mechanism are listed below. Since the Pleistocene deposits (glacial and lacustrine deposits) are not recent, the prevailing sediment transport mechanisms were interpreted based on their sedimentological and morphological characteristics and previous studies. However, the Holocene deposits (fluvial deposits, alluvial fan deposits, a debris flow deposit, and talus slope deposits) are being deposited today in situ and the descriptions of transport mechanism present our direct fieldwork observations, therefore the interpretation is not needed. Some of the above-listed deposits have been anthropogenically reworked on the surface. Areas of anthropogenically reworked deposits are defined as a morphological feature and not as a separate deposit type.
3.1.1. **Glacial deposits**
Sedimentologically, glacial deposits in the Planica-Tamar Valley are classified as tills. They are typical diamicton composed of unconsolidated poorly sorted sub-angular grains ranging from silt/sand size to big boulders of a few tens of cubic metres in volume. Till sedimentary bodies have an undulated terrain morphology and are located at several locations in the valley floor (Main Map). The most prominent and largest one is located in the central part of the valley floor covering approximately 70 ha. This body forms a topographic ridge of undulated terrain up to 30 m high, orientated in a north–south direction, covered by vegetation and well-developed soil and without outcrops of pre-Quaternary bedrock (Figure 2, Main Map). This till ridge is easily distinguished from other sedimentary bodies at the northern, eastern, and western sides, however it gradually transits into fluvioglacial deposits at the south. Apart from the largest ridge, there are also minor side ridges composed of till with undulated terrain (usually orientated in a north–south direction) located at the eastern and western side of the largest ridge. They are unconnected to the largest ridge-shaped sedimentary body and have heights reaching up to 10 m.

Based on the sedimentological features (chaotic architecture, clast size range from silt to few 10 cubic metres large boulders), their location and clast lithology analysis these sediments are of glacial origin (Bohinec, 1935; Jurkovšek, 1987a, 1987b; Triglav Čekada et al., 2015). However, the morphology and location of the largest ridge-shaped sedimentary body are enigmatic. Namely, they are located in the part of the valley where the predominant bedrock lithology of surrounding upper slopes is represented by Conzen Dolomite (Gale et al., 2015). However, a significant proportion of clasts belong to Dachstein Limestone, which is located at the southern and topographically higher parts of the valley more than 2 km from the ridge location (Gale et al., 2015). This large distance together with sedimentary characteristics and relatively low surface inclination rule out all other transport mechanisms except a glacial one. On the other hand, the peculiar morphology (i.e. large dimension and especially the position of the ridge in the central part parallel to the axis of the relatively narrow valley) is difficult to assign to a particular glacier valley moraine type (cf. Benn & Evans, 2010; Schomacker, 2011; Bennett & Glasser, 2009; Evans, Phillips, Hiemstra, & Auton, 2006; Eyles & Rogerson, 1978; Lukas & Rother, 2016). We suggest this ridge-shape morphology relates to the subsurface morphology of the pre-Quaternary bedrock onto which till deposited.

3.1.2. **Lacustrine deposits**
Lacustrine deposits are composed of horizontally laminated to thin-bedded fine-grained carbonate sand and silt (Figure 3), defined as lacustrine sediments of Pleistocene age. In the past, lacustrine deposits in the Planica-Tamar Valley, also referred to as lacustrine chalk in some Slovenian literature, have been briefly exploited (Bohinec, 1935; Jurkovšek, 1987b). Today they are outcropping only in one small topographic depression marked in our Main Map and are significantly anthropogenically reworked. Local geographic names such as Nova Kreda, Stara Kreda, and Na ilu (New Chalk, Old Chalk and ‘At the clay’), defining small topographic depressions indicate several other locations where these sediments are also present below a thin layer of Holocene sediments (Bohinec, 1935). Our fieldwork confirmed that such locations are today covered either by fluvioglacial deposits, alluvial fan deposits, or talus slope deposits.

3.1.3. **Fluvial deposits**
Fluvial deposits are composed of porous, unconsolidated, washed-out, sub-rounded, moderately to well-
sorted open framework sands and gravels to small sub-rounded boulders, and are bound to topographic depressions and plains. Morphologically, they form areas of levelling with active or inactive torrential channels.

Permanent surface water flows are not present in the Planica-Tamar Valley. The fluvial channels are represented by short torrential channels functional only during high precipitation events and snowmelt. After a short surface flow, water quickly infiltrates underground. Due to the high energy of torrential flows, these channels sporadically transport large amounts of sediment which is deposited in the areas of levelling.

3.1.4. Alluvial fan deposits

Alluvial fan deposits in the Planica-Tamar Valley are forming sedimentary bodies of alluvial fans (cf. Collinson, 1996; Nichols, 2009) which cover the middle and lower parts of the valley slopes and extend to the valley bottom (Main Map). They show the most complex sedimentary structure of all the sedimentary deposit types in the research area. Alluvial fan sediments are unconsolidated open framework gravels and sands with different texture and structure related to their position on the fan. In the proximal fan parts, the sediment is composed of unstratified, clast-supported, poorly sorted, very angular to angular open framework gravels, with large blocks up to a few cubic metres in size (Figure 4(a)). Middle fan parts are characterised by angular to sub-angular clast-supported, moderately sorted, open framework sandy-gravels. Individual clast size can be up to a few tens of centimetres. In the distal fan parts sediments are composed of sub-rounded, moderate to well-sorted clasts, of either clast-supported open framework coarse sands and gravels or matrix-supported sandy-gravels with a fine-grained sand matrix. Here sediments are organised into lenses and layers up to a few tens of centimetres thick (Figure 4(b)), with presence of sediment structures such as thin-bedding, cross-bedding, normal grading, and clast imbrication. Layers and lenses of distinct dark brown paleosoils (up to 20 cm thick) are also present in the middle and distal parts of some alluvial fans (Figure 4(c)).

Alluvial fans in the Planica-Tamar Valley have a radius up to a few hundred metres, a distinct fan shape (Main Map, Figure 5) and a catchment area in the hinterland mountain. Catchment areas normally have an up to two times larger surface area compared to their corresponding alluvial fans. The smallest fan has an approximate surface of 0.85 ha and a corresponding catchment area of 1.1 ha, while the largest alluvial fan has an approximate surface of 25 ha and a corresponding catchment area of 45 ha. From the catchment areas, the feeder channels emerge onto the fan surface where they become distributary channels (Figure 5). At the proximal fan part, distributary channels are usually narrow and incised into the fan body with depths of over 5 m. At this fan part, sieve deposits can be found (Figures 4(d) and 5). In the middle fan part, channels become wider and shallower, with depths varying from 1 to 5 m, where they form braided channel systems that migrate onto the surface of the fans. In the distal part of the alluvial fans, the channels become even wider and shallower (less than 1 m) and sometimes form an anastomosed channel system, where sedimentary fan-shaped lobes and sheets develop (Figure 5).

The morphology and sedimentological architecture of the fan are closely related to the prevailing sediment transport mechanism. An individual fan is fed by feeder channels or canyons that funnel the water and sediment from the higher lying fan catchment areas. During snowmelt and regular annual precipitation events, the sediment is mainly transported as bedload or in a suspension onto the fan surface. During periods of heavy precipitation, movement of the sediment is related to debris floods or sheetflood events (cf. Hungr, 2005; Hungr, Evans, Bovis, & Hutchinson, 2001), with their transport energy decreasing downwards. These events form sieve deposits or fan-shaped lobes and sheets, which differ in their sedimentological structures, size, and position on the fan surface. Sieve deposits are composed of angular to sub-angular, open framework, clast-supported, well-sorted, large gravels or blocks a few centimetres in size, and are typically found in the proximal and middle fan parts. They are usually bounded by a prominent channel and form several overlying fan-shaped deposits a few tens of metres wide and long. The relative age of an individual sieve deposit can be determined from clast surfaces weathering, as older clasts have a dark coating or are covered by lichens (Figure 4(d)). In contrast to sieve deposits, fan-shaped lobes and sheets are composed of sub-rounded, clast-supported, moderately sorted sands, and smaller gravels. Typically, they are present in the middle and distal parts of fans and can be up to one hundred metres long and tens of metres wide. They can be either confined in the braided or anastomosed channel systems where they can overlap each other or they can be unconfined and develop an avulsion event of an individual distributary channel (Figure 5). The relative age of an individual sheet and lobe can also be determined from clast surface weathering. Layers and lenses of paleosoils present in middle and distal parts of some fans indicate longer transport and sedimentation inactivity between depositional events (Figure 4(c)).

According to classifications by Collinson (1996) and Nichols (2009), the majority of alluvial fans in the Planica-Tamar Valley can be classified as sheetflood fans based on previously described sedimentary structures, morphological features, and the prevailing sediment transport mechanism.
3.1.5. Debris flow deposit

Debris flow deposit is present in one large recent debris flow fan in the Planica-Tamar Valley located on the western slopes of the Ciprnik Mountain (Figures 1, Figure 6(a), and Main Map). The debris flow fan (cf. Collinson, 1996; Nichols, 2009) is composed of unconsolidated, angular, very poorly sorted sediment whose fraction varies from clay size grains to blocks of a few cubic metres. The distribution of larger clasts within the debris flow sedimentary body is chaotic. The clasts belong to the Conzen Dolomite and the Tor Formation (Šmuc et al., 2015; Zupan, 2013; Figure 6(b)). The sedimentary body of a debris flow is deposited on top of the alluvial fan as a debris flow fan lobe, which at present forms a few metres high topographic ridge (Figure 6(c)).

The debris flow, triggered due to extremely heavy precipitation on the night from 18th to 19th November 2000, is an example of a complex slope mass movement. At first, it travelled as a translational movement on the slip plane of saturated Tor Formation clay layers near the peak of Ciprnik (Šmuc et al., 2015). Later on, the already deposited debris flow fan was partially eroded and deposited into several distinct units described by Župan (2013), Šmuc et al. (2015), and Briški (2016). The most distinct unit is the so called mud-lake (Figure 6(d)) composed of washed-out sand to mud fraction, which travelled as a mud flow down the valley towards the north (Briški, 2016; Šmuc et al., 2015). In the geomorphological map, the area of the ‘mud-lake’ is divided from the active fan-shaped body by an assumed boundary. Sedimentological analysis and radiocarbon dating of the ‘mud-lake’ show that, prior to the mud flow in the year 2000, several fluvial processes have occurred at that site, which are dated after the year 1850 and are defined as recent (Briški, 2016).

3.1.6. Talus slope deposits

Talus slope deposits are composed of clast-supported, very angular, and poorly sorted gravels, which have accumulated under steep valley cliffs. The majority of the talus slope deposits are deposited directly on fluvial deposits or alluvial fans and are morphologically separated with a distinct slope knickline, with talus...
slopes having significantly steeper surfaces in comparison with alluvial fans and fluvial deposits (Figure 7).

Sediments on talus slopes are fed mainly by rock fall. Typical scree deposits form in areas with active deposition, while talus slopes with inactive sedimentation are covered by vegetation, although minor rock falls still occur in those areas.

3.1.7. Anthropogenically reworked deposits
Surficial sedimentary deposits have been anthropogenically reworked by human activity due to the construction of infrastructure such as roads and paths. These areas are too small to be mapped on the scale of our map, however, there are three areas where Quaternary deposits were extensively reworked. Although they are modified, we were still able to identify the deposit type prior to reworking. The first area is located near the Tamar hut where fluvial deposits were reworked to create cattle pastures. The second area is the location of the exploited lacustrine deposits. The third and largest area is in vicinity of the Planica Nordic Centre, where glacial and alluvial fan deposits were extensively reworked during construction. During our fieldwork, parts of the Nordic Centre (west side of the valley) were inaccessible due to construction works, therefore those areas are mapped only as anthropogenically reworked deposits. Due to the complex nature of anthropogenically reworked deposits our method of classification based on sedimentological characteristics and transport mechanisms does not apply. Since they cannot be defined as a separate type of Quaternary deposits we regard them as a morphological feature.

3.2. Cross-section over the Planica-Tamar Valley
The cross-section runs transversely over the valley in a west–east direction (line A–B on Main Map). It is 1000 m long and represents a profile of five different Quaternary sedimentary deposit types (talus slope, active and inactive parts of alluvial fans, lacustrine deposits, and the largest sedimentary body of glacial deposits) and the pre-Quaternary bedrock, which does not outcrop at the valley floor. However, it does on both sides of the valley and at the cross-section location it is composed of Julian Conzen Dolomite (Gale et al., 2015). We assume the same lithology...
composes the pre-Quaternary bedrock at the cross-section location. Based on the topographic profile of the cross-section, the slope inclinations for Holocene sedimentary deposits (alluvial fans and talus slopes) vary from a few degrees to up to 15° for alluvial fans, and from 20° to 40° for talus slopes. The slopes of the largest ridge-shaped sedimentary body of glacial deposits have a gentle dip with inclinations that do not exceed 10°.

The cross-section tentatively presents the complex depositional geometry of the sedimentary bodies as well as a general relative spatio-temporal deposition reconstruction. In that sense, the Quaternary sedimentary deposits are deposited onto the pre-Quaternary surface. Since the latter is not visible anywhere on valley floor, the thickness of Quaternary sedimentary deposits is unknown and marked as assumed. The underground boundaries between individual sedimentary bodies are also unknown. Pleistocene sedimentary deposits (glacial and lacustrine deposits) were the first to be deposited on the bedrock, followed by intercalated Holocene sedimentary deposits (alluvial fans, fluvioglacial deposits, and talus slopes), which are deposited directly onto Pleistocene sedimentary bodies and the pre-Quaternary surface. We assume that in the valley subsurface Holocene deposits onlap onto Pleistocene deposits and pre-Quaternary surface, while different types of Holocene deposits are intercalated with each other, depending on which transport mechanism prevailed at a certain time. However, cases of onlapping Holocene deposits (talus slopes onto alluvial fans and fluvioglacial deposits) are possible, as presented in Figure 7.

4. Conclusions

The Planica-Tamar Valley is a typical alpine valley with present-day shape and morphological features that are a result of bedrock geology and sedimentation processes in the Quaternary period. In the Pleistocene, the main sedimentation process was controlled by
ice in the form of a mountain glacier, which deposited large amounts of glacial deposits during its retreat and gave the valley its typical U-shape with a relatively flat floor and steep slopes. In the Holocene, different sedimentation processes started to prevail, with gravity and water-driven erosion and transport. Today the valley slopes and floor are covered by different sediments, which are continuously being deposited in the most recent time in a response to local climate and bedrock geology. Sediments differ in their transport and deposition and form sedimentary bodies such as fluvial, talus slopes, debris flow, and alluvial fan deposits, each with its own distinct morphological and sedimentological features. The result of the Pleistocene and Holocene sedimentation processes is a complex depositional geometry of sedimentary bodies, which form the present-day landscape of the Planica-Tamar Valley.

Our study provides a spatial distribution and sedimentary characteristics of the different types of sedimentary deposits. Since very little research has been done regarding the Quaternary sediments, our work provides the basis for their further analysis in the research and broader alpine area. The sediments transported and deposited by Holocene sedimentation processes also present a natural hazard. On one hand, deposition in the area of alluvial fans and fluvial deposits caused by regular annual precipitation events blocks and damages the local roads, leading to constant repair works. On the other hand, heavy precipitation can cause debris floods or sheetflood events and can also trigger debris flows as observed in the case of the Ciprnik Mountain event (Šmuc et al., 2015). Such events pose a substantial threat to the infrastructure and human lives and can therefore cause a potential social and economic disruption. By mapping and identifying the different Quaternary deposits, our research offers a helpful tool and information regarding slope mass movement and natural hazard risk assessment in this area.

Software

The geomorphological map of the Planica-Tamar Valley was produced in QGIS 2.8 and the topographic terrain surface was extruded using the QGIS Terrain profile plugin. Additional features and map adjustments were drawn in Adobe Illustrator CS6.

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