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GLACIAL AND PROGLACIAL DEPOSITS OF THE RESIA VALLEY (NE ITALY): NEW INSIGHTS ON THE ONSET AND DECAY OF THE LAST ALPINE GLACIAL MAXIMUM IN THE JULIAN ALPS.

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ABSTRACT**:** The Resia Valley is located in the south-eastern sector of the Alps, where small glacial remnants are still preserved despite the average low-elevation of the reliefs. The abundance of glacigenic deposits related to the Last Glacial Maximum allowed to discuss and reconstruct the onset and decay of the glaciation. The initial glacier expansion from the Canin-Toudule and the Barman cirques led to the infilling of the former valley with fluvioglacial and glaciolacustrine successions. Then, the spread of the Resia Glacier during the LGM climax covered and over-consolidated these units. On the valley flanks, the interaction of the base of the trunk glacier with the sharp pre-glacial topography caused the formation of subglacial deposits containing large-size sub-angular boulders and glaciolacustrine fines. During the LGM the Resia Glacier reached the maximum thickness of about 550 m, and was tributary of the Fella Glacier at Resiutta. During the Late Glacial, two main stadial phases are characterised by frontal moraines and ice-dammed deposits. In the first, glacier streams flowed down only from the Resartico and Barman valleys, damming the trunk valley; this caused the formation of lakes and the aggradation of the outwash deposits related to the glaciers located in the upper valley. In the second stadial phase, glaciers were confined in high-elevation accumulation areas. Nevertheless, the Barman and Canin-Toudule ice streams reached the base of the slope, due to the peculiar climatological setting. In fact, the accumulation area is in one of the highest precipitation rate sector of the Alps (present MAP > 3000 mm). These climatological characteristics allow the preservation of very small glaciers, glacierets and firn-patches at about 2300 m a.s.l. even under the present, warmer climate.

Keywords: Glacial deposits, paleoglaciology, geomorphology, LiDAR DEM, Last Glacial Maximum, SE Alps.

1. INTRODUCTION

The south-eastern sector of the Alps (namely Carnic and Julian Alps) was characterised by a considerable extensive glaciation during the Last Glacial Maximum (Van Husen, 1987; Ehlers & Gibbard, 2004; Vai & Cantelli, 2004; Monegato et al., 2007; Carton et al., 2009; Bavec & Verbič, 2011) and even today some small glaciers and glacierets are still present at the lowest altitude (between 1830 and 2340 m a.s.l.) of the entire mountain chain (Serandrei Barbero et al., 1989; Carturan et al., 2013; Colucci & Guglielmin, 2014). In the southern part, at the boundary between the Julian Prealps and the northern Dinarides, several small cirque glaciers related to the last glaciation were recognised (Monegato, 2012; Žebre et al., 2014); they indicated a very low equilibrium line altitude (ELA) during the Last Glacial Maximum pointing to a very humid condition and, hence, enhanced the precipitation rates as marked also by pollen records (Pini et al., 2010). The preservation of a large end-moraine system at the outlet of the Tagliamento Valley (Fig. 1) led to the recognition of distinct advance pulses and glacier stabilisation phases during the last glaciation (Monegato et al., 2007; Fontana et al., 2014). However, the sedimentary evidence of the onset and decay of the LGM is very scarce in the mountain basins (Venturini, 2003; Bavec et al., 2004), even though the presence of glacial deposits is widespread and has been mostly related to the climax and decay of the last glaciation. The Resia Valley (Julian Alps and Prealps), a major tributary in the Fella catchment, contains thick remnants of glacigenic deposits; some of these were already ascribed to pre-Würmian glacial advances (Desio, 1926), but mostly related to the last glaciation and its decay (Zanferrari et al., 2013).

The present paper is aimed at depicting glacigenic deposits of the Resia Valley and its geomorphological evolution from the onset of the LGM to the present day. Sedimentological and stratigraphic analyses coupled with LiDAR data examinations cast a new light on the glacier development and decay in this sector of the Alps. In addition, considerations about the past and future development of accumulation areas in this boundary sector of the Alps are provided.

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Resia River basin (Fig. 1) is 105 km^2 wide and is located at the boundary between the Julian Alps and Prealps, in the south-eastern sector of the Alpine chain close to the boundary with the northern Dinarides. The Julian Alps are characterised by carbonate massifs, reaching the highest elevations in the Mount Triglav (2864 m a.s.l.) in the Slovenian side, and the Mount Montasio (2754 m a.s.l.) in the Italian side. The water divide between the Adriatic Sea and the Black Sea crosses the range of the Mount Canin (2587 m a.s.l.). Its western side represents the headwall of the Resia Valley (Fig. 1). The bedrock is made up of Upper Triassic carbonate succession, mainly dolostones (Dolomia Principale) and limestones (Dachstein Limestone), with Carnian red clay and gypsum (Travenanzes Fm.) cropping out along the valley (Carulli, 2006; Zanferrari et al.,

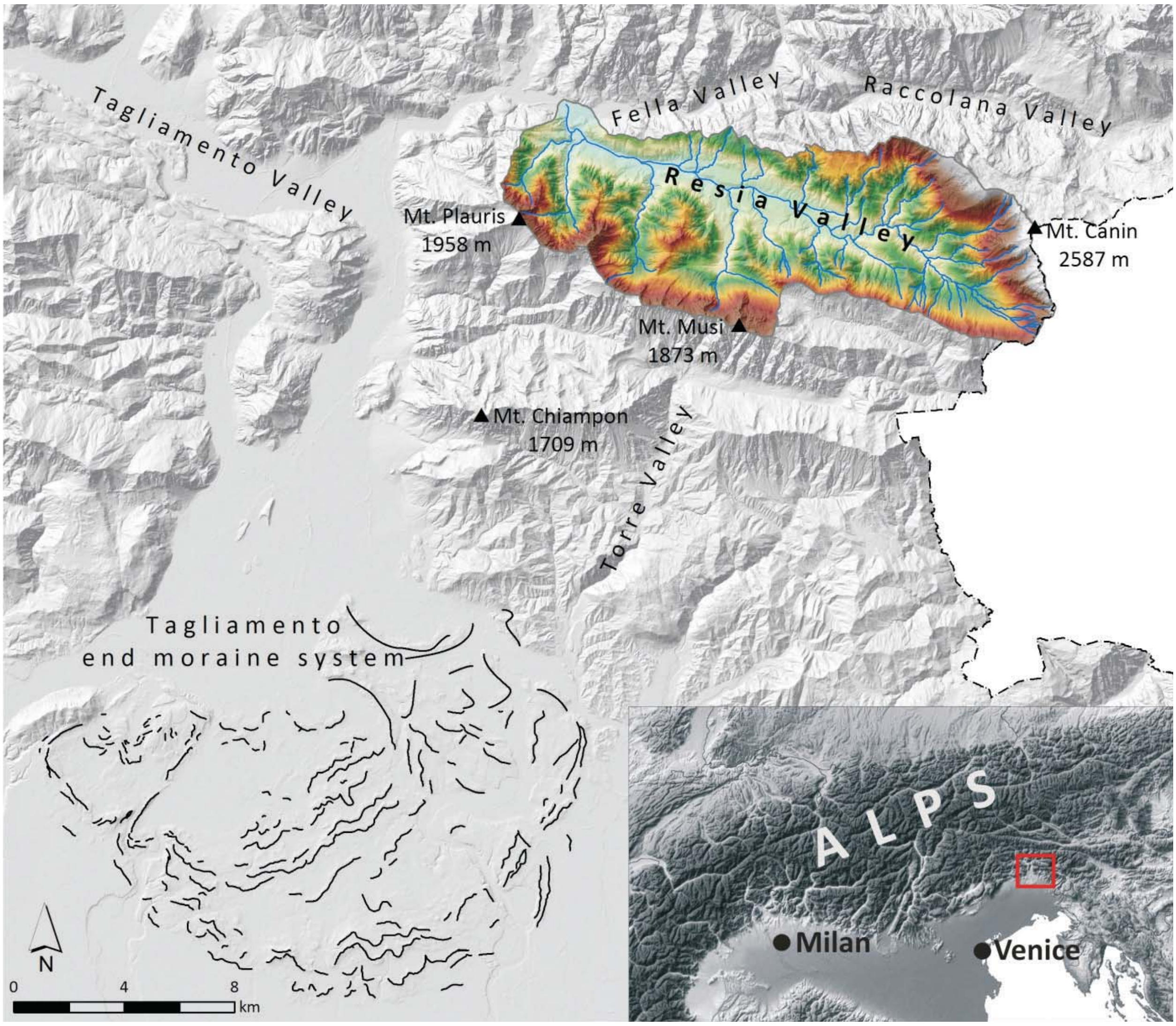

Fig. 1 - Location of the Resia Valley in the eastern Southern Alps. The dashed line represents the border between Italy to the left and Slovenia to the right.

2013). Jurassic to Cretaceous limestones, marly limestones and flysch crop out in the Barman Valley, a left tributary of Resia located in the Julian Prealps (Fig. 2). Here, the general northward dip-slope of the strata of about 55° is marked by the presence of well-exposed bed plains along the northern side of the Mount Musi. The Resia Valley is crossed by several faults related to the Idrija strike-slip system showing a WNW-ESE direction. These faults split the carbonate succession in slices and produce a sector of thick cataclastic deposits, that are partly inherited from the Dinaric phase of the Alpine orogenesis (Zanferrari et al., 2013 and refs. therein).

The geological and structural framework influenced the morphology of the Resia Valley, about 20 km long, whose direction follows that of the Resiutta fault of the Idrija system (Zanferrari et al., 2013). Also the main ridge of the Mount Musi and Plauris-Lavara (Julian Prealps), as well as the northwestern ridge of the Mount Canin have a direction inherited from this setting. However, the deep canyons of Barman and Nero creeks have a N-S direction.

The northwestern ridge of the Mount Canin is flat and includes the Mount Posar (948 m a.s.l.) and the Mount Plagna (853 m a.s.l.); it separates the Resia Valley from the lower Raccolana and the Fella valleys (Fig. 1). The upper valley is characterised by the steep western wall of the Mount Canin, even if the true head has lower elevation ending at ~1640 m a.s.l. The latter also represents the water divide with the Soča/Isonzo catchment, reaching even lower altitudes at Carnizza saddle (1086 m a.s.l.) in the upper Barman Valley.

The Quaternary successions are widespread along the valley, and have been reported since the late 19th century (Taramelli, 1875; Brückner, 1891; Tellini, 1891). A more detailed description was provided by Desio (1926), who recognised the presence of pre-Würmian successions at Gniva, Oseacco and Coritis.

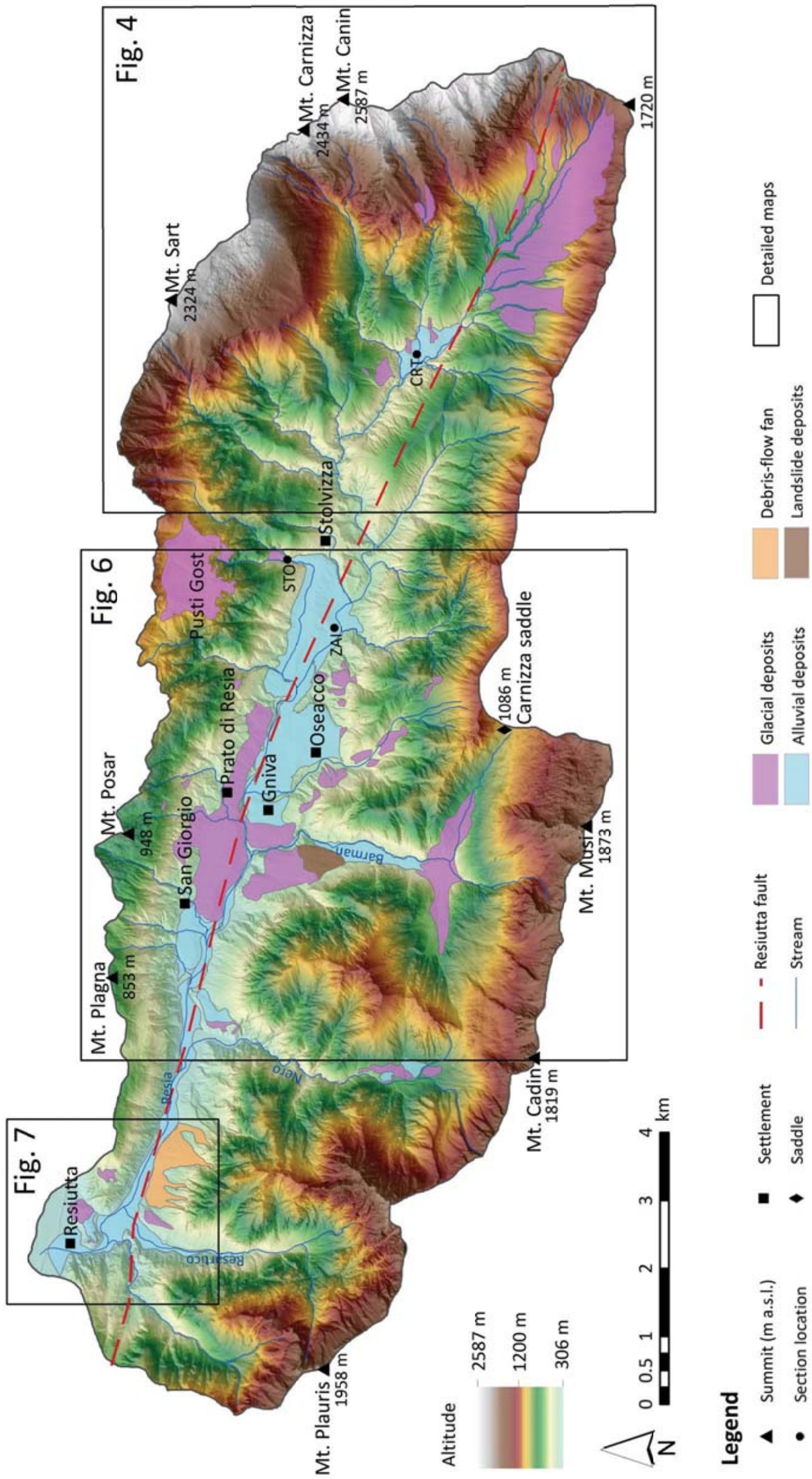

Fig. 2 - Contour DEM of the Resia Valley with the distribution of the major sedimentary bodies. In black frames the area investigated in detail: Fig. 4: Upper Resia Valley; Fig.6: Barman/Resia junction and terraces; Fig. 7: Outlet of the Valley at Resiutta.

Fig. 3 - The Toudule cirque in September 2006 (ortophoto, left) and in August 2014 (oblique view, right), respectively after an "average" and "above average" precipitation winter season.

The same author gave a description of the glacial deposits related to the Würmian and to the following ice-decay. He highlighted the presence of "exotic" boulders from the Carnic Alps in the upper Resia Valley. He related these findings to glacial transfluence from the Fella catchment, but this would implied anomalous flow of the glacier streams. A synthesis was reported in the official geological map of Italy at the scale 1:100.000 (Gortani & Desio, 1925) that evidenced the abundance of deposits along the valley floor, but very scarce patches of glacial deposits on the flat northern divide. Later investigations documented the presence of deformation in the lacustrine deposits at Oseacco and Coritis (Vaia & Zorzin, 1981; Cavallin & Martinis, 1985) tentatively ascribed to neotectonics, as well as the presence of older valley outlets at different elevations, evidenced in recent studies (Battello & Vaia, 1999; Zanferrari et al., 2013).

3. CLIMATOLOGICAL SETTINGS

The area of the Julian Prealps is known for being a region of heavy precipitation in the Alps where particularly large annual mean values are observed (Isotta et al., 2014). The 1981-2010 Mean Annual Precipitation (MAP) shows a peak of 3335 mm on the Canin Massif at 2200 m a.s.l., (Colucci & Guglielmin, 2014), representing one of the highest mean values for the Alps and Europe (Gregorcic et al., 2001; Norbiato et al., 2007). In the valley bottom the 1961-2000 MAP of Resia (380 m a.s.l.) and Oseacco (490 m a.s.l.) is equal to 2458 mm and 2620 mm respectively, while in the village of Musi (635 m a.s.l.), slightly southern of Mt. Musi (1866 m), is equal to 3035 mm (open access data OSMER-ARPA FVG). Snow is also very abundant in the area, especially over the Canin Massif with a mean winter snow accumulation of 7.0 m at 1830 m a.s.l.. Available data for Coritis (641 m a.s.l.) shows a 2001-2013 mean annual air temperature (MAAT) of 9.8±0.6°C (open access data OSMER-ARPA FVG). The 1981-2010 MAAT for the Mt. Canin (at 2200 m a.s.l.) has been recently estimated in 1.1±0.6°C (Colucci & Guglielmin, 2014). These peculiar climatological characteristics still allow the existence of some very small glaciers (*sensu* Kuhn, 1995), glacierets and ice patches at very low altitudes on the northern side of Mt. Canin, developing between 1830 and 2340 m a.s.l.. Also on the sunny-southern slopes in the Resia Valley, at highest elevation, some snow patches persist till the end of the ablation season in some years giving indications about how the onset of a glaciation might develop in the Resia Valley. This is particularly evident in the Toudule cirque (Fig. 3). The avalanche activity plays of course an important role, mainly owing to the topography of the northwestern slopes in the orographic left of this cirque. The widespread avalanche activity is aided by the presence of several gullies able to drive and canalize avalanches practically during and after any snow event. This leads to the accumulation of large snow masses at the base of the rockwalls often able to counteract the summer heat. This is also facilitated by the higher shading thanks to the north-westerly aspect. Since the end of the Little Ice Age (LIA) both MAAT and mean summer air temperature in the Canin area, reconstructed at 2200 m a.s.l., have risen of about 1.5°C showing an accelerated trend in the last 2 decades. During the 1970s and 1980s there is evidence of a higher frequency of snow-ice fields remnants, supported by private photographic material and personal communications given by the local population and the park authorities. These fact lead to conclude that during the LIA some permanent ice field or even very small avalanche-fed glacier or glacieret could have been existed, in a time when the Canin glaciers were covering an area of about 1.2 km^2 instead of the current 0.2 km^2 (Colucci & Guglielmin, 2014).

Other potential areas for the formation of glaciers are identifiable in the north-facing slopes of the Resartico and Barman valleys, below the Mount Musi and Mount Plauris (Fig. 2), where widespread snow fields recently survived at the 2009 and 2014 summer heats.

4. METHODS

The stratigraphy of the sedimentary units is established using the allostratigraphic approach (NASCN, 1983); outcrop description was performed and synthesised using fluvial (Miall, 1996) and glacial (Eyles et al., 1983) facies codes.

The geomorphological map was obtained not only from fieldwork mapping, but also from geological maps (geological sheet 049 "Gemona del Friuli" at the scale 1:50.000; Zanferrari et al., 2013) and Geographic Information System (GIS) analysis of orthophoto and LiDAR data. The Resia Valley area was surveyed by airborne laser scanning between 2009 and 2010 by the Civil Defense of FVG using a LiDAR system Optech ALTM 3033 having laser frequency of 33 kHz and a laser wavelength of 1047 nm. The minimum point density is 4 point m^{-2}, and the relative horizontal and vertical accuracies are better than 1 m and 0.3 m, respectively. The acquisition mode picked up simultaneously the first and the last pulse and the intensity, particularly important in forested areas. Each survey has been performed in late summer and early autumn, when no fresh snow was present on the ground, with exception of some very small patches at the highest altitudes (Fig. 3). This is clearly visible also from high resolution (0.15 m px^{-1}) aerial photographs acquired during the flights, and even used for the identification of geomorphological features.

A digital elevation model (DEM) having posting of 1 m px^{-1} has been obtained, and an extensive use of shaded reliefs derived from the DEMs (hillshade) for helping the identification of the past glacial features has been made.

The equilibrium-line altitude (ELA) was determined by applying the accumulation-area ratio (AAR) method. The AAR method requires a contoured map of the former glacier surface and the ratio of the glacier's accumulation area to the sum of its accumulation and ablation areas (Benn & Lehmkuhl, 2000; Porter, 2001). Well preserved frontal moraines and evident accumulation area allow the accurate reconstruction of the glacier surface and thus the calculation of the ELA only for the Barman Glacier. Although the average AAR for the glaciers in the European Alps was found to be 0.67 (Gross et al., 1976), in this study lower AARs were used for the ELA calculation due to the assumed debris cover and avalanching effect.

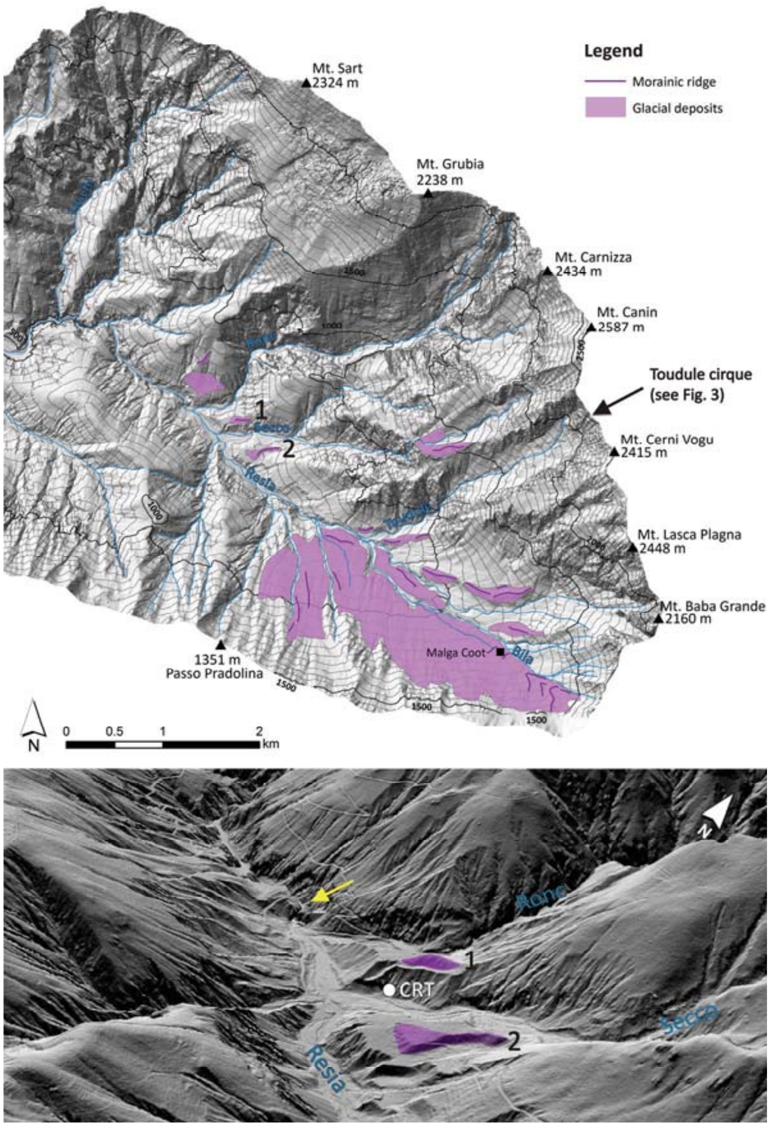

Fig. 4 - Geomorphological map and 3D LiDAR image of the upper valley. The yellow arrow indicates the narrow gorge of the Resia River downstream the terraces; 1: Hudaraven moraine; 2: Coritis moraine.

5. GEOMORPHOLOGY OF THE RESIA VALLEY

The upper Resia Valley is characterised by the presence of a cirque complex (Fig. 4), having a role of accumulation area in the past. The majority of cirques are not well-developed and are characterised by a widespread system of gullies and incisions. Their present morphology is prone to avalanche activity, being especially high on the south exposures, where very steep slopes, exceeding even 60 degrees, are common.

On the north-westernmost part a widely extended plateau between the Sart (2324 m a.s.l) and Grubia (2238 m a.s.l.) peaks, reaching the lowest altitudes at ~1500 m, separates the Laschi cirque from that of Ronc (Fig. 4). In both cirques no clear evidence of moraine deposits can be recognized probably owing to steep slopes and high avalanche reworking. The Laschi cirque is completely and deeply dissected by gullies, meanwhile the Ronc cirque is the largest and most well-developed cirque in the upper Resia Valley (Fig. 4) The latter is also the highest cirque, reaching the top of the headwall in the peak of Canin (2587 m a.s.l.). Here, avalanches can start from an elevation up to 2400 m, following the path of the Ronc Creek and reaching even

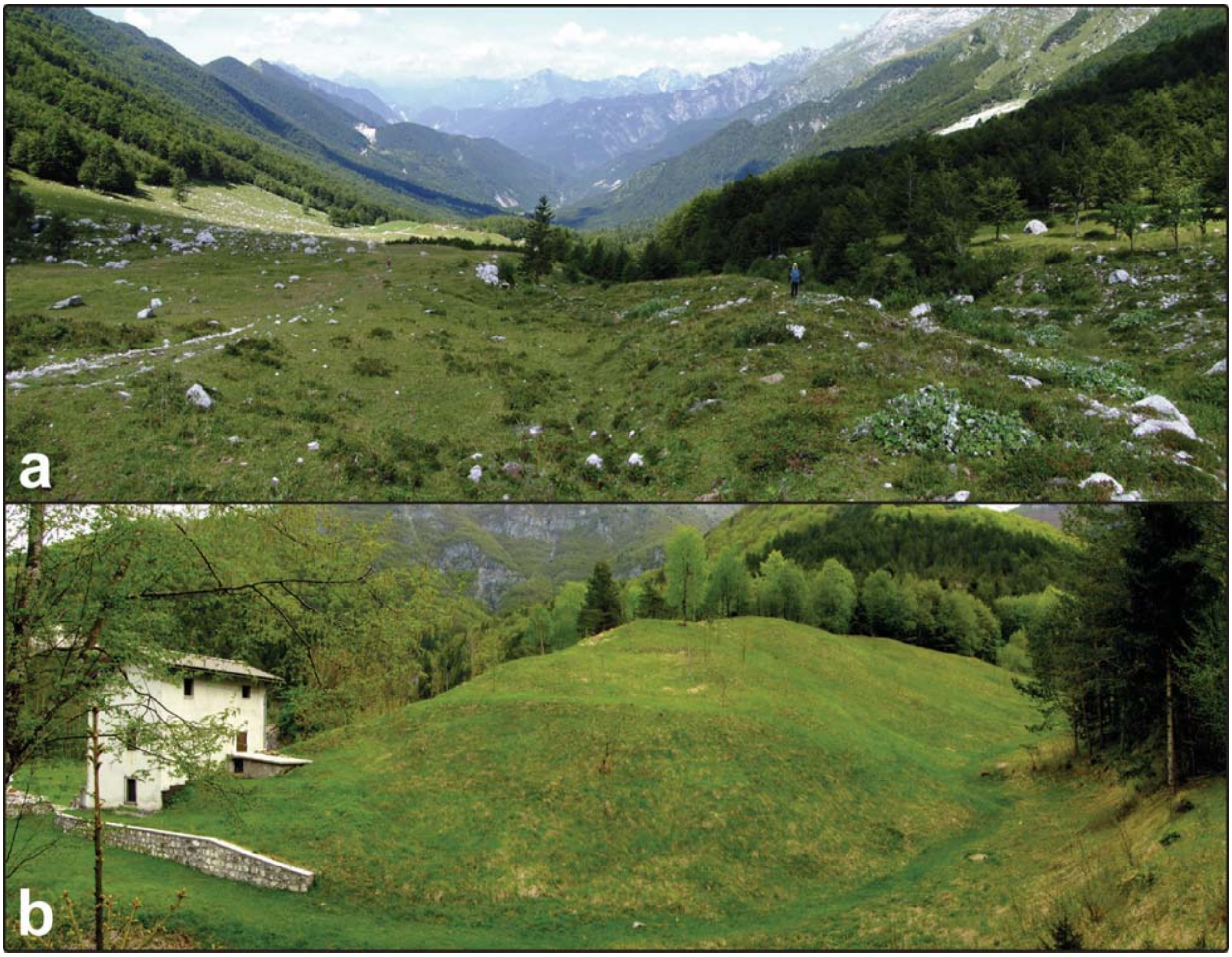

Fig. 5 - a) The upper cirque at Malga Coot with moraines related to the Late Glacial. b) The Hudaraven moraine at the outlet of the Ronc

the valley bottom at ~600-700 m a.s.l. At the outlet of the Ronc valley, on the orographic left, a 130 m long and ~25 m high moraine ridge (Fig. 4), interpreted as the lateral moraine of the Ronc glacier, is present on the fluvial terrace at 625 m a.s.l.. Glacial deposits on the orographic right are scattered along the slope between 610 and 830 m a.s.l. Here, only one moraine ridge between 755 and 830 m a.s.l. can be distinguished. South of the Ronc cirque the 0.3 km wide and 1.5 km long Secco cirque-like feature is present, extending between 1350 and 2570 m a.s.l. It ends with two lateral moraines ~320 m long. Below the Secco cirque, more than 200 m high cliff leads to the Secco valley, that reaches the confluence with the Resia River at 565 m a.s.l. (Fig. 4). Two evident ridges are present on both left and right fluvial terraces, extending up to 65 m above the present Resia riverbed. Neither one of those two ridges is interpreted as belonging to the glacier coming from the Secco cirque due to its small accumulation area (Fig. 4). The moraine ridge to the right, at Hudaraven (1 in Fig. 4; Fig. 5b) probably belongs to the glacier coming from the Ronc valley (as already discussed), meanwhile the moraine of Coritis (2 in Fig. 4), located between 650 and 690 m a.s.l., is interpreted as a right lateral moraine of a trunk glacier coming from innermost sector of the valley. Further to the south-east another narrow, but relatively well-developed and NE-SW elongated cirque, named the Toudule cirque, is present between the Canin (2587 m a.s.l.) and Cerni Vogu (2415 m a.s.l.) peaks. On the orographic left, at the base of its north-west and west slopes, there is evidence of the only semi-permanent snow patches in the Resia Valley at about 1900 m a.s.l., still existing with the present climatological conditions (Fig. 3) and related to avalanche feeding. This phenomenon is of great importance, since we can assume that during the glacial phases this glacier cirque was among the most active in the area. Moraine deposits coming from the Toudule cirque are preserved up to 80 m above the present Toudule valley bottom, where avalanche activity is absent. They appear in the form of both, right and left (Fig. 4) lateral moraines, extending between 820 and 1000 m a.s.l.

Between the Mt. Lasca Plagna (2448 m a.s.l.) and Mt. Baba Grande (2160 m a.s.l.), another former glacial accumulation area is present, although missing the typical cirque morphology. Like the majority of the cirques in the study area, also this one is characterised by a high avalanche activity. Evident lateral moraines occur below the cirque at 1300 m a.s.l. The right one is at least at two sides breached by avalanche tracks coming from the steep south-facing slopes below the Mt. Lasca Plagna. The left lateral moraine is dissected by small streams, thus its morphology is preserved only in the upper- and lower-most part. Both orographic left and right lateral moraines end at ~900 m a.s.l. The lowest cirque in the upper Resia Valley is located in the south-easternmost part of the valley, actually representing the only one with a series of well-preserved terminal moraine ridges. This cirque is longitudinally divided by the Bila Creek, and around the Malga Coot (Fig. 5a), in the virtually southern portion, well-preserved glacial deposits are present. The three most evident ridges develop between 1270 and 1485 m a.s.l. (Fig. 4). Two more ridges at 1170 and 1205 m a.s.l. are preserved down valley, also interpreted as belonging to the Malga Coot glacier, since all the ridges are present on the orographic left of the Bila Creek. The entire north-facing slopes, between the creek flowing from the Passo Pradolina saddle (1351 m a.s.l.) towards north and the Malga Coot cirque, are covered by glacial deposits, mainly reworked by avalanche activity. The majority of the ridges in this sector are the result of avalanche paths, with ridges in between. Only few of them are of glacial origin.

The water divide between the Resia and Fella valleys has a ESE-WNW trend from the Mt. Canin. At Pusti Gost (Fig. 2) a wide plateau is present. It is covered by erratic boulders of Dachstein Limestone, while the moraines show a weathered top with reddish, partially colluviated soil (7.5YR Munsell). No exotic boulders from the Fella catchment are present.

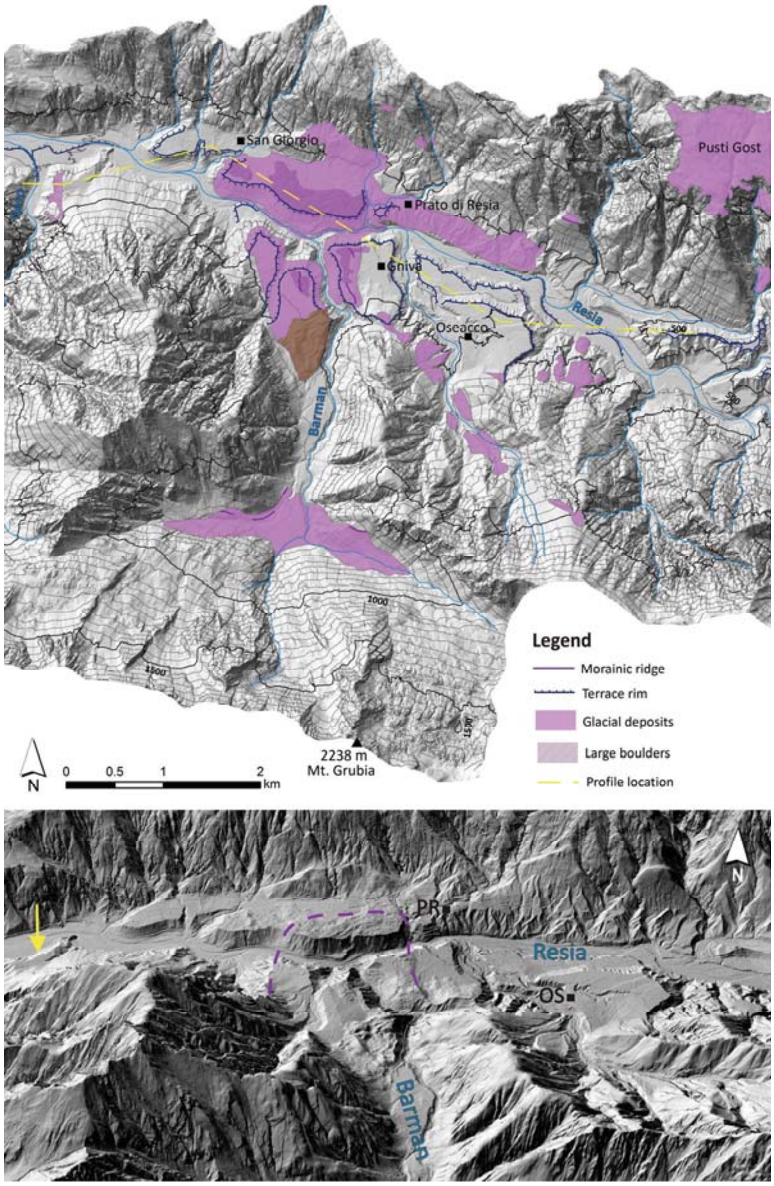

Fig. 6 - Geomorphological map and 3D LiDAR image of the middle Resia Valley at the junction with the Barman valley. The yellow dashed line is the trace of the longitudinal profile of Figure 8. Purple dashed line indicates the rim of the Barman moraine; the yellow arrow indicates the right wing of the Nero Fan. OS: Oseacco; PR: Prato Resia.

The middle-lower part of the Resia Valley is mainly characterised by the sequence of terraces (Fig. 6). They extend between the settlements of Stolvizza and San Giorgio. The Stolvizza alluvial terrace is positioned between the Resia River to the south and the Potoch Creek to the north. It is the highest among the series of terraces with the top between 540 and 570 m a.s.l. It is rising approximately 100 m above the present Resia riverbed, while only 50 m above the Potoch Creek. Downstream, on the left bank of the Resia River at the Oseacco settlement, a staircase of terraces is present. Two evident terraces can be recognized: the upper one with the top at 500 m a.s.l. and the other one 60 m below. Their tops are completely made up of alluvial deposits. Other smaller terraces are located next to the river bed between 415 and 420 m a.s.l. Further downstream, another terrace at 465 m a.s.l. with the Gniva settlement on the top (Fig. 6) is positioned on the left bank of the Resia River. About 50 m of incision formed by the stream flowing from the valley to the south, separates the Gniva terrace from the Oseacco terrace. The top of the eastern part of the Gniva terrace is covered by alluvial deposits, meanwhile the western one is characterized by glacial deposits containing large boulders. Moreover, two small ridges up to 15 m high and 200 m long, extending in the N-S direction, can be recognized on the top of the terrace. Another flat surface to the west, separated from the

Gniva terrace by the 70 m incised Barman River, extends between 475 and 530 m a.s.l. Also this terrace has large boulders scattered on the surface and one ridge with the N-S orientation. Going from the terrace upstream to the Barman Valley, glacial deposits are covered by deposits made up of boulders, as visible also from the undulate morphology they form (Fig. 6). These deposits cover the area of 0,19 km^2 and can be ascribed either to a landslide fallen on the Barman Glacier or to a postglacial landslide coming from the slopes of the Monte Colc (759 m a.s.l.) at the orographic left of the Barman Valley.

North of the confluence between the Resia and Barman rivers a large terrace at 450 m a.s.l. is present at the right side of the valley. It extends between the San Giorgio and Prato di Resia settlements. Up to 10 m large boulders are scattered only along the edge of the terrace, while the other, northern part of the terrace surface is flat. The boulders are present also in the Resia River bed below the terrace. These large boulders can be traced upwards to the terraces at the outlet of the Barman River and, together with the ridges there situated, have been interpreted as belonging to a frontal moraine system from the Barman Valley. In the latter, some inner moraines are preserved in the wide flat area at the foot of the Mt. Musi northern slope.

The last evident terrace is present west of the San Giorgio settlement. The top of the terrace is between 410 and 420 m a.s.l. Its surface is made up of coarse alluvial deposits (Fig. 6). Down valley, at the confluence between the Resia River and Nero Creek, a large outwash fan was formed by the latter. Its remnants can be recognized in the orographic right of the Nero Valley outlet, between 400 and 500 m a.s.l., where they cover glacial deposits. The last among the southern tributaries of the Resia River is the Resartico Creek (Fig. 7). At the orographic right of the Resartico outlet the ridge between 380 and 435 m a.s.l. is a lateral moraine, extending up to 30 m above the present valley floor, ascribed to the Resartico glacier. Along the left slopes of the Resia Valley between the Resartico and Nero creeks, large debris-flow fans were formed (Figs. 2 and 7) due to steep slopes and thick cataclastic deposits along the Resiutta fault (Fig. 2). Some other glacigenic deposits scattered along the Resia Valley do not form clear geomorphological features and are therefore described only from a sedimentological and stratigraphic point of view in the following chapter.

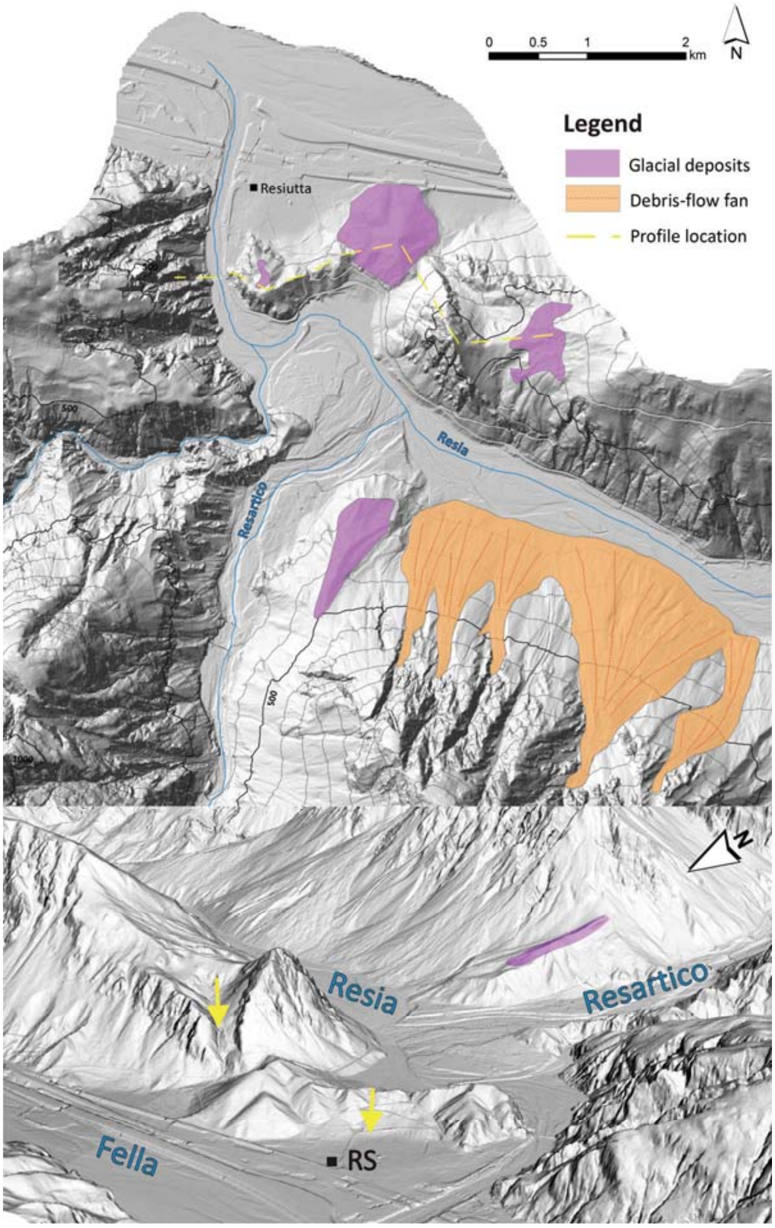

Fig. 7 - Geomorphological map and 3D LiDAR image of the outlet of the Valley at Resiutta. The yellow dashed line is the trace of the cross section of Figure 13, the two palaeo-outlet are highlighted (yellow arrows). RS: Resiutta

6. SEDIMENTOLOGY AND STRATIGRAPHY

The glacigenic deposits are distributed along both sides of the Resia Valley and have a discontinuous thickness depending on bedrock shape and presence of junction with tributaries (Fig. 2). The morainic ridges recognized in LiDAR images were checked on the field and the description of the deposits is generally reported. The main sections are described in detail, namely going downstream: Coritis, Stolvizza, Oseacco-Zamlin, San Giorgio-Gniva and Resiutta; here the superposition of different units provided the key relationships for unravel-

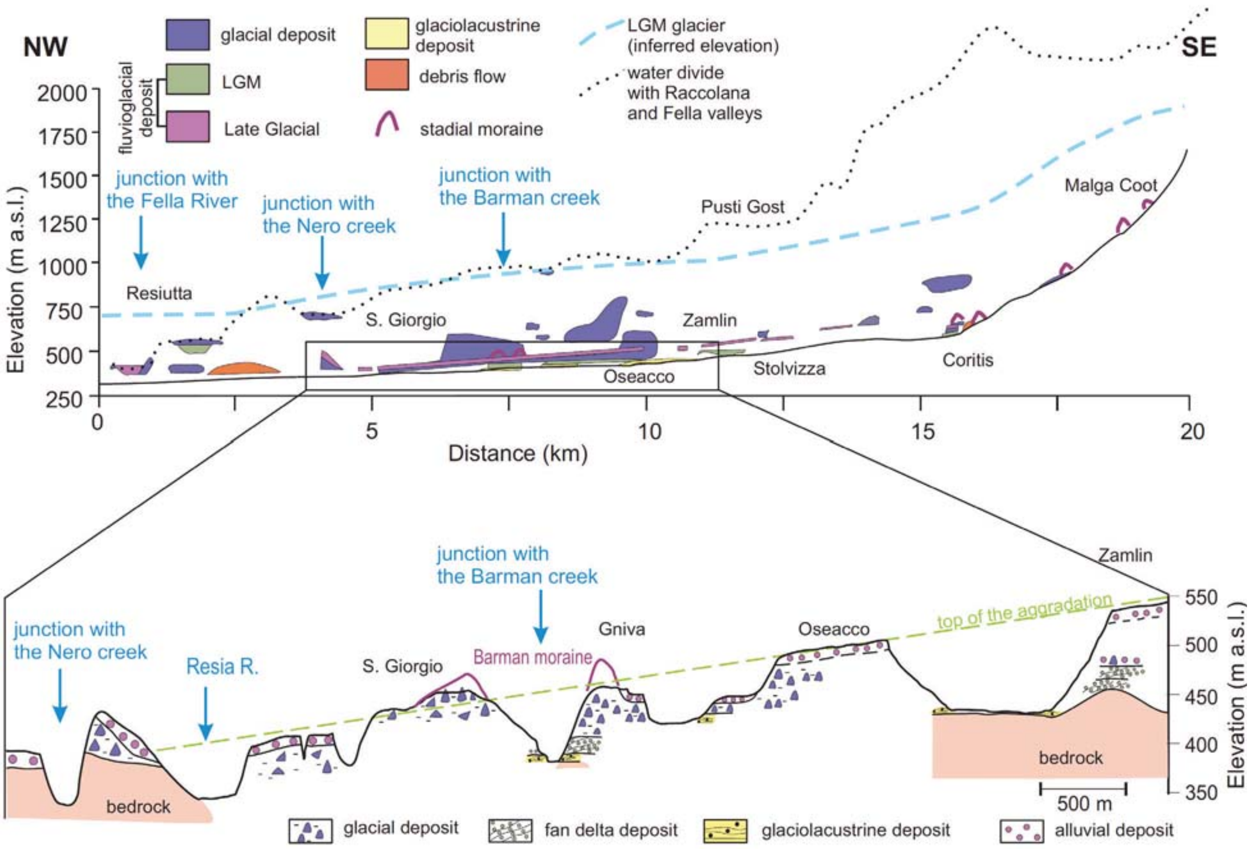

Fig. 8 - Longitudinal profile of the Resia Valley in which the sedimentary bodies and the moraines are plotted. Detail on the reach from Zamlin to the junction with the Nero Creek where the green dashed line represents the top of the Late Glacial aggradation driven by the damming of the Barman glacier and the development of the Nero Creek fan.

ling the evolutionary steps. These sections are correlated with the other scattered outcrops along a longitudinal profile (Fig. 8) that better shows their distribution.

6.1. Coritis

The Coritis section crops out in the upper Resia Valley (Fig. 4), about 0.5 km northwest from the Coritis settlement. It is located on the right side of the Secco Creek, near the confluence with the Resia River. The outcrop is about 60 m wide and around 45 m high. The section consists of six main stratigraphic units. They are described from the bottom to the top as follows (Fig. 9).

CRT-A: this unit is ~20 m thick and is composed of horizontally bedded deposits. The lower boundary is not visible since it is covered by talus debris. This unit consists of horizontally-bedded gravels (Gh) clast-supported and heavily consolidated. Clasts are sub-angular to sub-rounded, with average size from 1 to 2 cm, but the largest clasts range from 20 to 50 cm. The majority of the clasts are of local origin, although many exotic clasts can be found within the unit; these are sub-rounded and show oxidation cortex. Also some fine-grained lenses of laminated to massive silty sand (Sm-Sl) are scattered within the gravels. The facies association can be interpreted as a proximal fluvial deposit. The lower boundary, defined also by the lateral outcropping bedrock, suggest the presence of a fluvial incision at least 300 m wide, substantially wider than the present 30 m of the modern incision.

CRT-B: this unit consists of laminated silt (Fl) of hazel colour (2.5Y Munsell colour), in which many sub-angular to sub-rounded dropstones (grain to boulder size) are present. The deposit is characterized by folding and is heavily consolidated. The lower boundary is undulated. The thickness varies from 1 to 2.5 m, reaching ~5 m in the north-eastwards sector of the section. The unit can be related to glacio- lacustrine environment, filling an undulate topography (Fig. 10a).

CRT-C: this unit is about 8 m thick. It is characterized by matrix-supported massive diamicton (Dmm) with grey silty matrix (5/10Y Munsell colour). Clasts are predominantly sub-rounded to sub-angular, containing boulders up to 100 cm in size (Fig. 10a). Many clasts are polished, striated and faceted. The deposit is heavily consolidated and shows some irregular horizontal planes likely related to shear stress. It is ascribable to a lodgement till in subglacial environment.

CRT-D: the unit is ~3 m thick and is made up of matrix-supported, bedded coarse diamicton with sandy matrix (Dms), boulders are concentrated in the lower part.

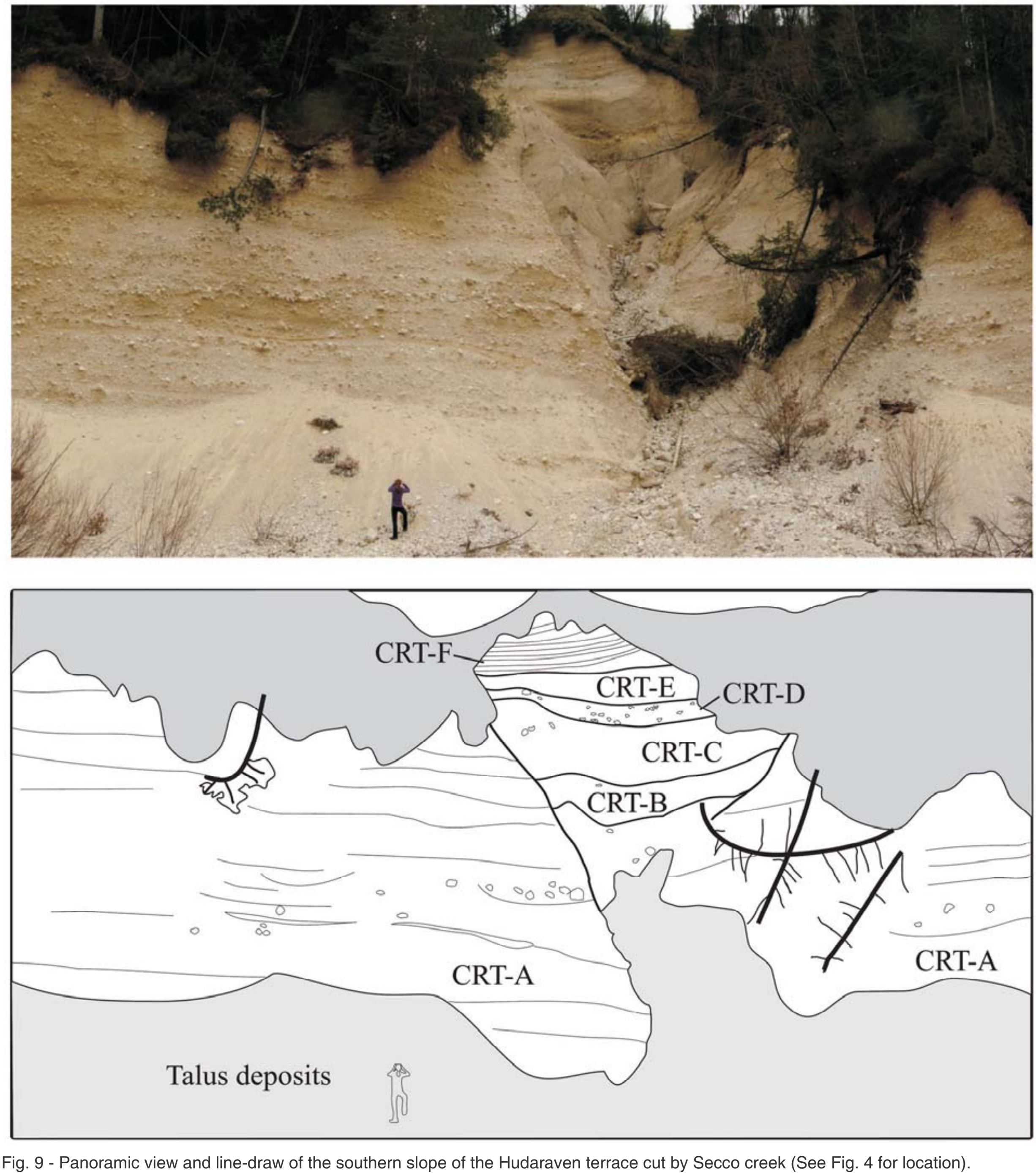

Fig. 9 - Panoramic view and line-draw of the southern slope of the Hudaraven terrace cut by Secco creek (See Fig. 4 for location).

Clasts are angular to sub-angular (Fig. 10b). The deposit is consolidated and can be related to a supraglacial till with evidence of subsequent reworking.

CRT-E: the thickness of the unit is ~4 m. Deposits are laminated silts and sands (Fl-Sh) of hazel colour (2.5Y Munsell colour). Deposits are not folded and only few dropstones are present within the layer. This body can be ascribed to lacustrine bottomset and the presence of dropstones suggests a proglacial environment.

CRT-F: the upper-most unit is made of 6 m thick, clinostratified graded gravels, in which the dip angle descreases toward the top (Fig. 10b). This unit consists of clast-supported coarse gravels. Clasts are predominantly sub-rounded and of local origin. Matrix is coarse sand. The deposit is unconsolidated and reaches up to the top of the slope. The deposit can be ascribed to the foreset beds passing to the topset of a

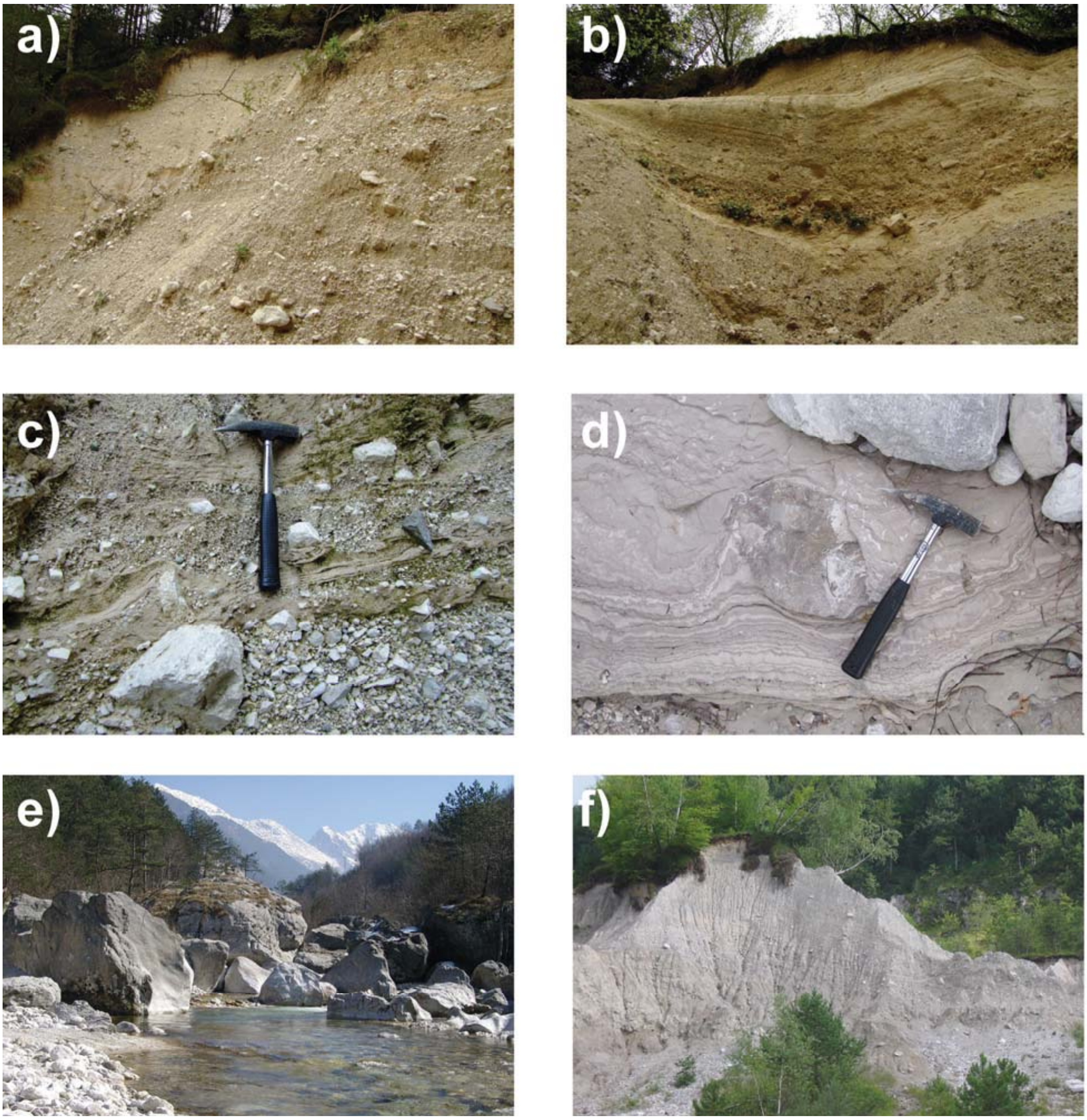

Fig. 10 - a) transition between over-consolidated glacio-lacustrine deposits (CRT-B) and the massive lodgement till (CRT-C) in the Coritis section. b) Close-up to the diamicton with angular pebbles (CRT-D) and the overlain glaciolacustrine (CRT-E) and deltaic (CRT-F) units under the Hudaraven terrace surface. c) Over-consolidated laminated fines with dropstones interbedded to massive diamicton (STO-B) in the Stolvizza section. d) Over-consolidated laminated lacustrine deposits with dropstones showing glaciotectonic deformations (Resia riverbed close to Oseacco). e) Boulders along the Resia River close to the junction with the Barman. f) Lateral moraine close to Oseacco in which the till shows a rough inclined bedding.

delta fed by a nearby outwash stream.

On the Hudaraven terrace a moraine is present close to the terrace. The related diamicton is rich in carbonate boulders. This moraine was likely deposited by a glacier tongue coming from the Ronc cirque (Fig. 4), damming the Resia Valley and forming a lake whose deposits are represented by units CRT-E and F.

6.2. Stolvizza

The section crops out along the Potoch Creek 300 m upstream of the village in correspondence to a waterfall, where the outcrop is 15 m high. A small earth pyramid is preserved downstream the waterfall. The section consists of four different units, whose description follows the line-draw of Figure 11.

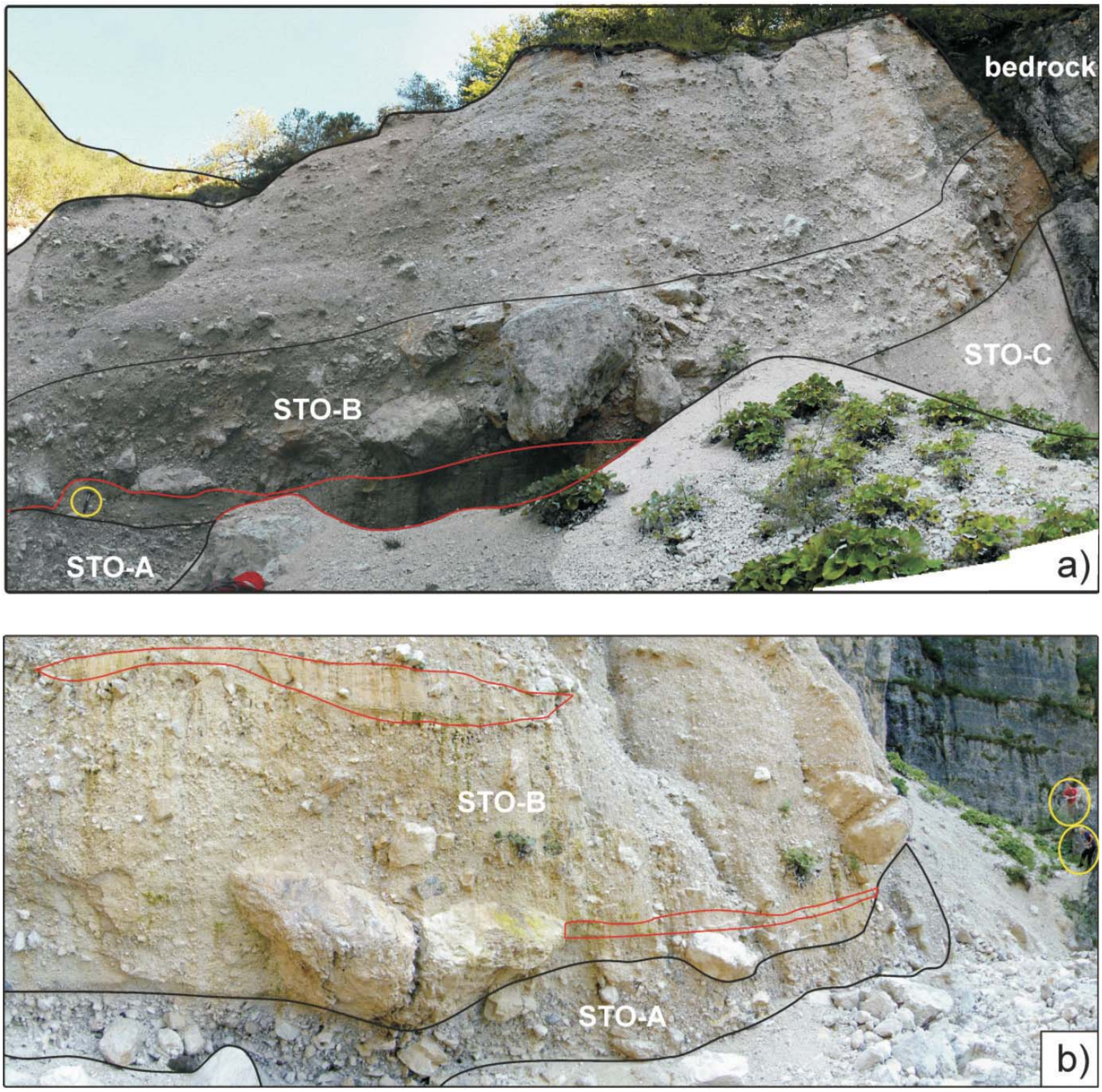

Fig. 11 - Panoramic view of the section along the Potoch creek close to Stolvizza, the glaciolacustrine layers are marked in red contours. a) E-W side and lateral boundary with the bedrock (hammer scale in yellow circle 40 cm long); b) N-S side to the left of the previous picture

STO-A: this unit crops out in the lowermost part close to the bedrock, it is made of matrix- to clast-supported massive diamicton (Dmm-Dcm), which includes small boulders (Fig. 11a) of limestone and dolostone, while exotic pebbles are scattered. Clasts are sub-angular to sub-rounded and many of them are polished and striated; matrix is silty sand. The deposit is heavily consolidated and the visible thickness is of about 1.5 m. The deposit can be generally interpreted as a sub-glacial till.

STO-B: the boundary with the previous unit is irregular, this deposit is heterogeneous and consists of matrix- to clast-supported diamicton, crudely clinostratified (Dms-Dcs) in metric beds, containing sub-angular to sub-rounded limestone and dolostone boulders 1 to 2 m large (Fig. 11b). Sub-rounded clasts of exotic lithologies are scattered. These look slightly weathered. The deposit is heavily consolidated. Three distinct layers of laminated silt (Fl), from 10 to 50 cm thick, are interbedded (Fig. 10c). The presence of sub-rounded to sub-angular clasts, striated and polished, deeply disturb the planar lamination and they are interpreted as dropstones. These layers are heavily deformed in folds and are also heavily consolidated. On

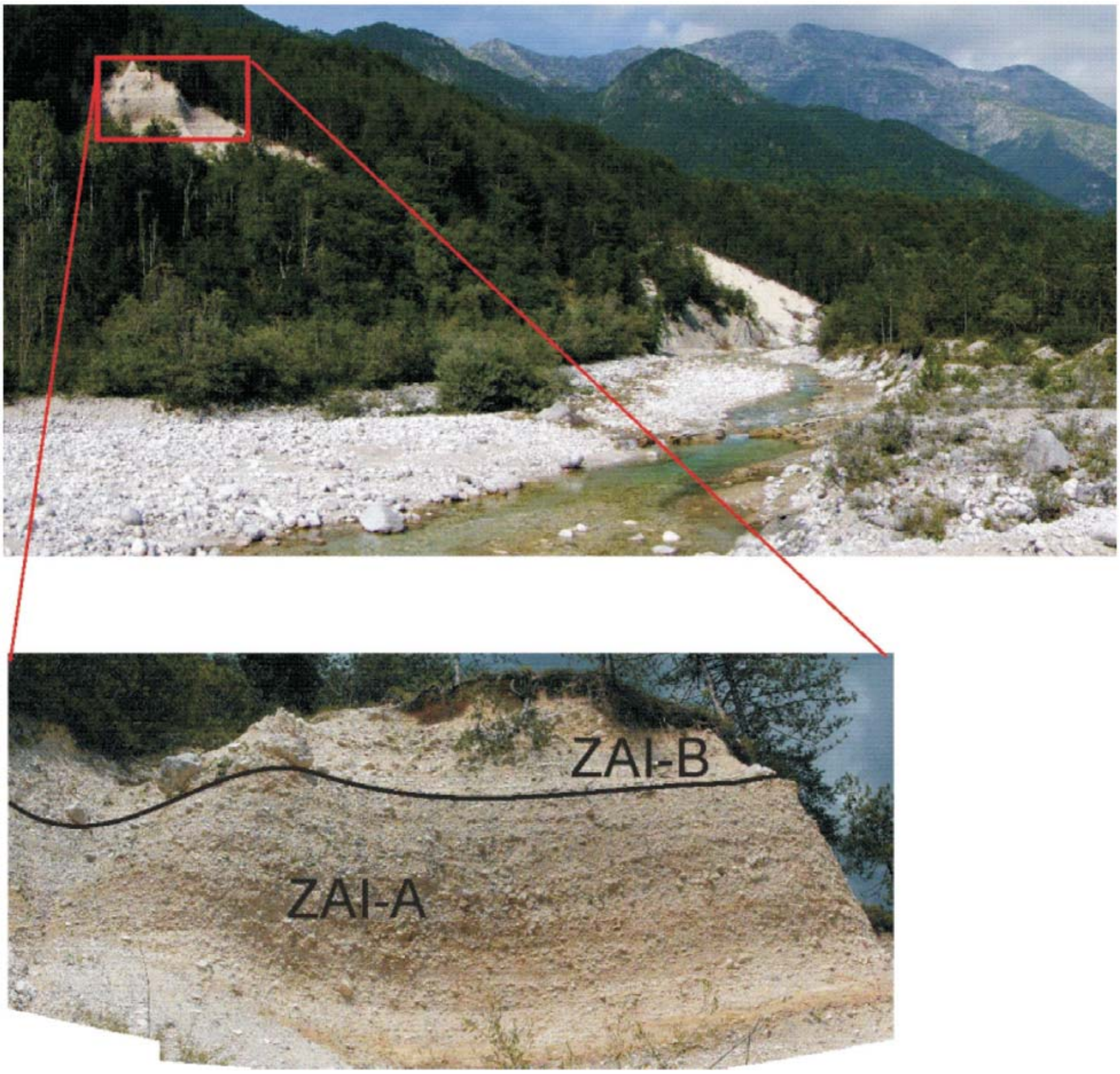

Fig. 12 - Panoramic view of the Zamlin terrace from the Resia riverbed, where the Carnian bedrock crops out, and zoom on the main es-

the whole, the thickness is about 12 m. The presence of lacustrine lenses with many dropstones within the diamicton complex can be related to the presence of small ponds in subglacial marginal environment.The clinoforms in the Dcs facies suggest the flowing of debris from the side of the glacier, while the deformation and the over-consolidation are related to the subsequent load of the glacier.

STO-C: this unit is confined between the previous one and the bedrock cliff close to the waterfall (Fig. 11a). The lateral relationship is hidden by talus deposits. The deposit is made up of clast supported gravel and sand (Gcs-Sl) showing a clinoforms (35°) towards the west, beds are normally graded and the clasts are sub-rounded to sub-angular, reaching the maximum size around 25 cm. The deposit is heavily consolidated. Close to the bedrock the dip increases to 60°. The thickness reaches 10 m close to the cliff. Considering the possible relationships with the other units, this deposit can be related to a small fan-delta confined between the bedrock and the ice in marginal or sub-glacial position. The increase of the dip angle close to the bedrock could be ascribed to the load of ice and sediments of unit STO-C on these deposits.

6.3. Zamlin and Oseacco

The Zamlin section (Fig. 12) is located along the Resia River upstream to the junction with the Potoch

Creek. The basal boundary of the Quaternary succession on the Carnian bedrock (dolostone, gypsum and red clays of the Travenanzes Fm.; Zanferrari et al., 2013) is irregular, as visible in the cross section of Figure 8.

The basal unit (**ZAI-A**) is made up of well bedded gravel, clast-supported and normally graded (Gl). The bedding shows a gentle dip towards the W. The clasts are sub-rounded, mostly made up of carbonate fragments, exotic clasts are scarce. Clast-size reaches 25 cm. The deposit is heavily consolidated and has a preserved thickness of 15 m. A 40 cm thick sandy layer slit the unit in two separate bodies showing the same sedimentological characteristics except for the progradation of the bedding, whose dip changes from W to WNW. It can be related to a progradation of a fan delta subsequently loaded by the advancing glacier.

The upper surface is sharp and erosive. The unit at the top (**ZAI-B**) is made up of a gravelly diamicton, clast-supported and crudely bedded with many boulders (Dcs). The visible thickness is about 7 m. The deposit can be ascribed to high energy regime in fluvioglacial environment. Because of the absence of outcrops in the upper portion of the terrace, from 490 to 537 m, it is not possible to determinate the effectiveness of the presence of a lodgement till related to the Resia glacier, as the overconsolidation of the basal unit seems to suggest. The topmost flat surface, is characterised by loose coarse gravels, clast-supported and crudely bedded, with sandy matrix.

Downstream of Zamlin, on the left bank of the Resia, a fine grained laminated silt (Fl), containing many sub-rounded to sub-angular clasts, some of them striated, lays on the Carnian bedrock. The visible thickness is about 4 m. The deposit is heavily consolidated and very deformed by folds and faults (Fig. 10d). Matrix -supported massive diamicton (Dmm), showing shear planes and containing many striated pebbles, is associated. For the whole stack a subglacial deposition of till and glaciolacustrine fines can be raised.

The left slope of the valley is characterised by matrix-supported massive to roughly bedded diamicton (Dmm-Dms) with boulders, from the bottom till about 670 m a.s.l. The top of the terrace from Stolvizza to Zamlin can be continuously traced along the Oseacco terrace (Figs. 6 and 8). Along the cut of the creek close to Oseacco, a section provides the architecture of the latter. At the bottom of the slope a fine grained laminated silt and sand deposit crops out (Fl), containing many sub-rounded to sub-angular clasts, some of them striated, interpreted as dropstones. The deposit is heavily consolidated and deformed by folds and small faults; the visible thickness is about 6 m. It intertongues with graded gravels, clats-supported and heavily consolidated (Gl-Gh). Clasts are sub-rounded and mostly made of carbonates, exotic clasts are lacking. The thickness is about 8 m. A sharp surface on the top cut this body and above a massive diamicton, matrix supported (Dmm) crops out. It is made of big boulders of carbonates in a sandy-silty matrix (2.5Y Munsell colour). The deposits is consolidated and has a visible thickness of about 15 m, it is interpreted as a subglacial till.

6.4. San Giorgio and Gniva

At Gniva, on the left bank of the Resia Valley, a long section crops out at the junction between the Resia and the Barman. Along the road fine grained laminated silt and sands crop out (Fl), containing many sub-rounded to sub-angular clasts, some of them striated, lay on the Carnian bedrock. The visible thickness is about 2 m. The deposit is heavily consolidated and very deformed, with folds and faults. They gradually pass to clinostratified graded gravels, clats-supported, locally cemented and heavily consolidated (Gl-Gh). Clasts are sub-rounded and mostly made of carbonates pointing to the Barman catchment while exotic clasts are lacking. The thickness is about 15 m. Also here a sharp surface on the top cut the gravel body; above a massive diamicton, matrix-supported (Dmm) crops out, made of sub-angular to sub-rounded boulders of carbonates in a sandy-silty matrix (2.5Y Munsell colour). The deposit is consolidated and has a visible thickness of about 15 m, and is interpreted as a subglacial till.

The clinostratified unit has been interpreted as a pre-Würmian deltaic deposit (Desio, 1926) buried by Würmian glacial units. Considering the over-consolidation and the cementation of the lowermost deposits, their relationship with the glaciolacustrine fines, they are interpreted as the infill of the valley during the widespread of the glacier at the onset of the LGM, whose sedimentary evidence is the upper diamicton.

The morainic ridges at the outlet of the Barman Valley cover the succession. These are made of matrix-supported massive diamicton (Dmm), with big boulders of carbonates; the silty-sandy matrix shows a pale yellow colour (2.5Y Munsell).

The right bank of the Resia River at San Giorgio is characterised by a basal fine grained laminated silt and sands (Fl), containing many sub-rounded to sub-angular clasts, visible for 2 m. It is overlain by graded gravels, clast-supported, locally cemented and heavily consolidated (Gl-Gh); the thickness is undetermined for the presence of cover debris. At the top of the terrace big boulders (up to 10 m large) are scattered on the surface close to the rim, while to the north the terrace surface is flat. The boulders show a petrographic signature from the Barman catchment and can be considered as erratics. The same boulders fill the Resia reach 700 m long (Fig. 10e).

6.5. Resiutta

At the outlet of the Resia Valley, near Resiutta, there are two successions filling concave base morphologies in the dolostone bedrock (Fig. 13). The first is about 100 m large, with the base at 470 m a.s.l. and filled by 40-m thick succession, starting with laminated sand and silt (Sl-Fl), unweathered (2.5Y Munsell colour), passing to a weakly cemented gravel, clast-supported and crudely bedded (Gh), clasts are sub-rounded and of carbonate petrography. Towards the top the bedding is better organized (Gp). The total thickness of this unit (**RES-A**) is about 30 m. The deposit is covered by 10 m thick unit (**RES-B**) made up of matrix-supported massive diamicton (Dmm); matrix is silty (10YR Munsell colour), clasts are sub-angular to sub-rounded, striated and polished; the petrography points to the Fella basin for the

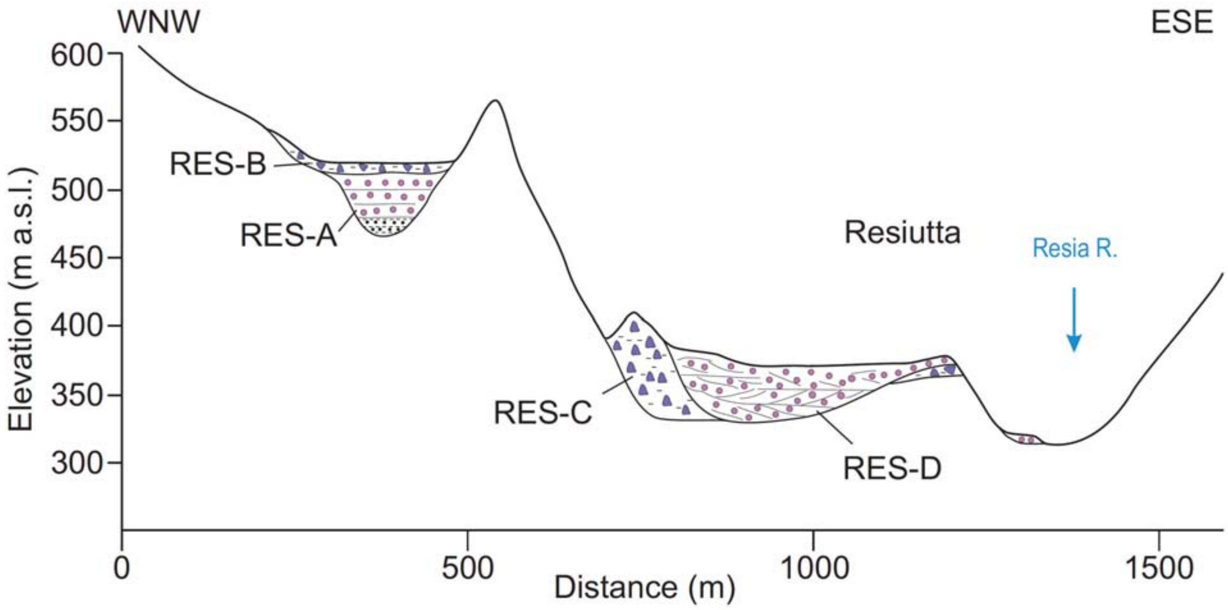

Fig. 13 - Cross section of the outlet of the valley at Resiutta (see Fig. 7 for location).

presence of many lithologies from the Paleocarnic chain. The unit RES-A can be ascribed to a filling from the Resia Valley caused by downstream damming by the Fella glacier, which subsequently deposited the subglacial till (RES-B) above.

The second succession crops out 500 m westwards. It is a 300 m large and characterised by two sedimentary units. Unit **RES-C** is made up of matrix-supported massive diamicton (Dmm) with many boulders and striated sub-angular to sub-rounded clasts,. The polygenic petrography indicates the provenance from the Fella catchment. The visible thickness reaches 90 m. The unit laterally lays on the bedrock in the eastern part of the section. A second unit (**RES-D**) has a lateral boundary with the previous; it is made of horizontally to planar cross-bedded gravels (Gh-Gp), weakly cemented; clasts are sub-rounded to rounded and made of carbonate lithologies belonging to the Resia Valley. The basal boundary on the dolostone bedrock is at 330 m a.s.l. for a preserved thickness of about 60 m. Also these two units represent a damming phase of the Resia valley from the Fella glacier, whose the elevation is about 150 m lower than the previous.

6.6. Other alluvial deposits

These deposits are scattered along the valley, from the outlet at Resiutta to Stolvizza (Figs. 2 and 8). They are made up of sandy gravels, horizontally crudely bedded (Gh), clast-supported; lenses of massive to trough cross-bedded sand (Sm-St) or silty sand are scattered. Clasts are sub-rounded. The deposits are in general normally consolidated. They are interpreted as the result of outwash streams during the withdrawal of the glaciers in the Late Glacial and the deposition of tributary creeks as the Barman and Nero.

6.7. Other glacial deposits

Along the valley many patches of chaotic diamicton, matrix-supported (Dmm) and normally- to over-consolidated are scattered. Rough inclined bedding can be present. These deposits are characterised by angular to sub-rounded clasts, faceted, polished and striated. Meter-size boulders are common. Matrix is a sandy silt (5/10Y to 10YR Munsell color). In the over-consolidated diamicton the silty matrix is very abundant, while the normally-consolidated is richer in sand. The first can be assumed as lodgement till, and its position is always close to the bottom of the succession. The second is widespread on the valley slopes, from the bottom to the highest elevation of these remnants, and can be related to supraglacial till related to lateral moraines (Fig. 10f). As shown by the longitudinal profile, the glacial deposits cover a belt from 350 to 800 m a.s.l. along the valley, while in the uppermost portion (the former accumulation area) they are present at higher altitude. The petrographic composition reflects the bedrock outcropping along the valley, and those related to the Barman tributary glacier are very rich in Jurassic-Cretaceous limestones. However, several sub-rounded pebbles and boulders of volcanites, quartz-conglomerates and green to red sandstones coming from the *Palaeocarnic Chain* (Venturini et al., 2002) can be recognised in the upper Resia Valley. It is remarkable that most of them show slight weathering or oxidation on the surface.

7. THE EVOLUTION OF THE RESIA VALLEY SINCE THE ONSET OF THE LGM

The abundance of glacigenic deposits in the Resia Valley is peculiar in the Tagliamento catchment, where the trunk valleys are filled with Late Glacial to Holocene fluvial and lacustrine successions (Venturini, 2003; Venturini et al., 2004; Monegato & Stefani, 2011). The presence of wide outcrops with overlapping sedimentary units provided new insights on the evolution of the valley at the onset of a glaciation and in the decay as well, as shown in the present study through geomorphological and sedimentological analyses, despite the lack of new datings. The stratigraphic reconstruction along the Tagliamento Valley (Zanferrari et al., 2013) provided good correlations with the LGM units of the Tagliamento end moraine system (Monegato et al., 2007).

7.1. Pre-LGM topography

The topography of the valley at the onset of the last glaciation can be inferred (Fig. 14a) from the short reaches filled by deposits that crop out at Coritis, along the Stolvizza-Zamlin area and at the outlet near Resiutta. The valley section at Coritis is presently about 40 m large, flowing in a 5-m narrow gorge just downstream of the Resia River - Ronch Creek junction (Fig. 4). The difference is related to the change in bedrock unit, from red clay and gypsum formation to dolostones. The former reach was about 200 m large, as evidenced by the alluvial filling of Unit CRT-A. It is remarkable that the basal surface of this paleotopography, at 575 m a.s.l., is lower than the flat top of the bedrock ridge at the gorge, located ~300 m downstream. Hence, a wide reach was present in the "soft" rocks sector also in the pre-LGM time, but it has to be assumed that the modern narrow gorge was already there at that time and survived to glacial quarrying and subglacial erosion. Further investigations are necessary for establishing possible neotectonics reasons.

Downstream, from Stolvizza to Zamlin, the modern Resia riverbed shifts westwards and cuts the bedrock in several right-angle reaches some hundreds of meters long (Fig. 4). At Zamlin, the filling succession clearly deepens towards the north, suggesting that the path of the river was located some hundreds of meters northwards (Fig. 14a). The basal surface at Stolvizza of the unit STO-A could represent a small remnant of the pre-LGM topography.

At Gniva the fan delta deposits have basal surface at 380 m a.s.l. These have been considered pre-Würmian "interglacial" in age (Desio, 1926; Cucchi & Finocchiaro, 2009), because of the cementation and deformation. However, their relationship with glaciolacustrine sediments at the Resia/Barman junction suggests a deposition during the onset of the last glaciations and implies a damming downstream.

At Resiutta (Fig. 13), two section at different elevation show a similar setting of fluvial deposits (RES-A and RES-D) belonging to the Resia Valley, whose aggradation was triggered by damming from the Fella Glacier, as testified by the glacial units (RES-B and RES-C) with basal surfaces at 470 and 330 m a.s.l. The modern Resia outlet is located 300 m westwards and has an elevation of 317 m a.s.l. The higher alluvial deposit can be related to a spillway during the LGM, then covered by the ice stream. However, it cannot be excluded that this path acted as valley outlet during the Middle Pleistocene. The second section is wider and filled by glacial deposits that made low elevated moraines at Resiutta (Battello & Vaia, 1999). These can be ascribed to a recessional stage of the Fella trunk glacier damming the valley. The basal surface at 330 m a.s.l. was likely the outlet before the LGM, with an elevation of about 10 m above the modern outlet of the river

7.2. LGM

The extent of the maximum development of the glaciers in the Tagliamento catchment and in its tributary from Resia Valley has been debated since Taramelli's (1875) pioneering work,. The thickness of the Tagliamento glacier at the Fella/Tagliamento junction has been interpreted to be up to 1000 m (Penck & Brückner, 1909; Castiglioni, 1940; Gortani, 1959; Van Husen, 1987; Venturini, 2003), while interpretation of thinner ice streams was lately speculated (Vai & Cantelli, 2004) and recently a ~650 m thick glacier was inferred (Zanferrari et al., 2013). The reconstruction of the Resia glacier provided by the distribution of glacial deposits yield a ~550 m thick ice stream (Figs. 8 and 14b), which covered most of the catchment and joined the Fella glacier in the lower valley. However, it did not reach the Pusti Gost plateau at 1200 m a.s.l. The abundance of heavily consolidated glacial but also glaciolacustrine and fluvioglacial deposits along the valley, from Coritis to Resiutta, yield information on the onset of the glaciation. The development of ice streams took place in an articulated longitudinal valley, with narrow reaches spaced by larger segment and with transverse junctions with north-exposed tributaries enhancing the development of many lakes created by glacier damming. Their preservation in some reaches of the valley is similar to the configuration of the onset of the last glaciation that was recently evidenced in the Austrian Alps in tributary catchments of the Inn Valley (Reitner, 2005; Reitner et al., 2010); here the development of glaciolacustrine and deltaic environments was related to the advance of the glaciers. Along the Inn Valley, despite the subsequent flow of the Inn Glacier, one of the largest of the Alps, succession related and dated to the late MIS3 are preserved (Starnberger et al., 2013a,b; Spötl et al., 2013).

The climax of the glaciation in the southeastern Alpine range lasted from ~26 to 19 ka BP as constrained by the oscillation of the piedmont lobe of the Tagliamento Glacier (Fontana et al., 2014). During this time span the Resia Valley was covered by flowing ice streams (Fig. 14b). The interaction of the base of the glacier with the sharp pre-glacial topography caused the presence of sub-glacial till containing big sub-angular boulders, as in the Stolvizza succession (Fig. 11). The connection with the Fella glacier took place in the Resiutta area. The major glaciers were the Barman and the Ronch, whose accumulation areas are below the western wall of the Mt. Canin. The ELA for the Julian Prealps (Mt. Chiampon area, Fig. 1) during the LGM was estimated at about 1150 m (Monegato, 2012). The calculation for the Resia Glacier is unreliable. However, the ELA for the Barman Glacier during the Late Glacial (see chapter 7.3) indicates a considerably lower elevation. The reconstructed configuration of the glaciers during the LGM makes the presence of exotic clasts in the upper valley through transfluences of the Fella glacier unconvincing, as already pointed by Desio (1926), who had to force an oversized Fella glacier into the Resia

Valley during the “Würmian glaciation”. Most of the exotic clasts show oxidation or weathering and their presence in the deposits (CRT-A and STO-B), related to the onset of the glaciation, make probable their primary deposition before the LGM during a middle Pleistocene glacial expansion, and their reworking during the LGM. The absence of exotic boulders in the Pusti Gost plateau is consistent with a lack of transfluence to the upper Resia Valley. In fact, the plateau remained outside the LGM deposition, as inferred by the weathering of the deposits of the Pusti Gost.

7.3. Late Glacial

The successions of the Resia Valley have been mostly considered as related to the Late Glacial since Desio (1926). For this reason a correlation with the classic Alpine stadials (e.g., Penck & Brückner, 1909; Ivy-Ochs et al., 2008) has been attempted so far (Desio, 1926; Venturini, 2003; Tintor & Andrič, 2014). Several advance pulses were recognised also in other sectors of the Tagliamento catchment and related to five definite stadial phases (from Bühl to Egesen) stratigraphically grouped in the “alte valli subsynthem” (Venturini et al., 2009). However, a clear attribution to the Alpine stadials becomes speculative without chronological constrains. In the Resia Valley at least two clearly distinct stadial advances were recognised (Fig. 14c and 14d), but a specific attribution to the Alpine stadials is unreliable.

The first stadial unit (Fig. 14c) was characterised by the spread of the southern tributaries that dammed the valley with the glacier (Barman and Resartico) or with the spread of outwash fan (Rio Nero). The Barman is the largest system and its advance formed a small frontal system at San Giorgio/Gniva sector. According to Desio this damming created a lake, whose lacustrine fines were recognized at Prato Resia (Figure 24 in Desio, 1926), while the valley upstream was filled by the outwash deposits of different ice streams flowing from the Mt. Canin and the wide accumulation area around Malga Coot. The presence of terraces downstream of the Barman moraines, as evidenced by the correlation of the tread of the terraces (Fig. 8), points to a damming by the outwash fan of the Nero Creek, whose east wing has a similar elevation. Finally, the elevation of the Resartico moraine in correspondence to the present Resia Valley floor suggests that also the Resartico Glacier dammed the lower reach of the valley.

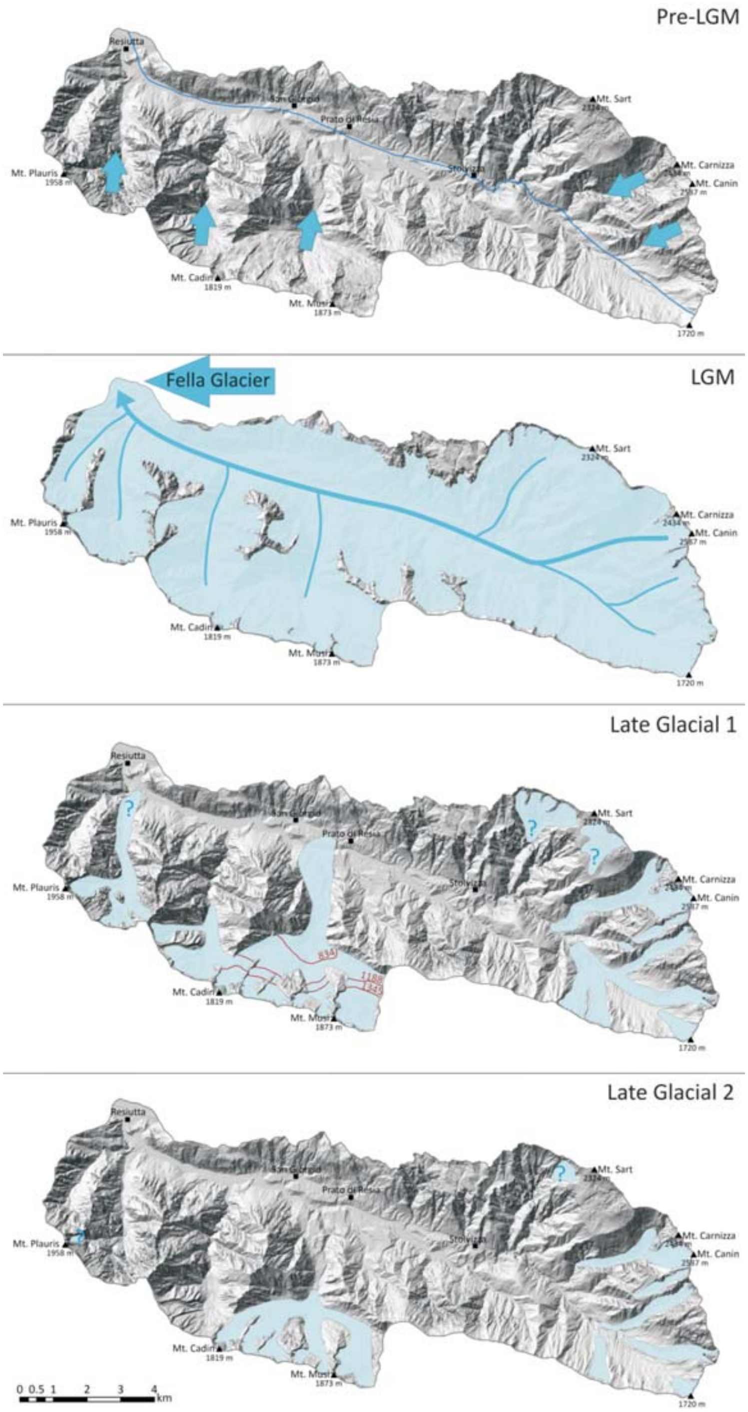

Fig. 14 - Reconstruction of the glaciers in the Resia Valley from the onset of the LGM to the Late Glacial. The blue line in the Pre-LGM indicates the possible path of Resia River, the blue arrows show the glacier initiation areas. The ELAs of the Barman Glacier in the Late Glacial 1 are marked with red lines.

In the second stadial phase (Fig. 14d) the glaciers were in general confined to the head of the valleys. However, in the upper Resia six single glaciers flowed till ~750 m a.s.l., while in the Barman Valley the glaciers probably even merged. At this time the terraces from Coritis to San Giorgio were already shaped by the incision of the drainage network.

The ELA of the Barman Glacier in the first stadial phase would be as low as 834 m a.s.l., considering the typical AAR (0.67) for the glaciers in the European Alps (Gross et al., 1976). Assuming a great amount of snow accumulation from avalanches, which is supported by the avalanche path distribution map, the AARs in the Barman valley were likely lower. We should also consider the influence of debris covering on the increment of the size of the ablation area, related to landslide activity in the terminal part of the valley and a general topographic setting with prevailing steep slopes. Using the AAR 0.3, the ELA would be at 1345 m a.s.l. This value is comparable to that calculated in the nearby Mt. Chiampon range in the Julian Prealps (~1370-1450 m) (Monegato, 2012). Even 1188 m a.s.l. (AAR 0.4) would be a reasonable value for the ELA of the Barman Glacier since in high mountain areas, the AARs could highly vary between glaciers even within small regions (Benn & Lehmkuhl, 2000). Moreover, the ELA of the Barman Glacier was probably the lowest one among the glaciers in the Resia Valley owing to a great topographic effect. Due to a lack of geomorphological evidence for calculating the ELA for the second stadial phase, we can only assume that the ELA was up to 100 m higher in comparison with the first stadial, as was found for the Mt. Chiampon range (Monegato, 2012).

8. CLIMATOLOGICAL CONSIDERATIONS ON THE ONSET OF THE GLACIERS IN THE RESIA VALLEY

Observations of the present evolution of some semi-permanent snow/firn patches, mainly formed by avalanches activity, allow to make some assumptions on the past (and future) onset of the glaciation of the Resia Valley. The glaciers probably start to form at the Toudule cirque, probably able to give birth to a fast growing tongue, and from the north facing slopes of Mount Musi and Plauris. Shaded aspect, high precipitation and avalanche activity are thus capable in supporting the growing of the glaciers in the higher and northerly aspects of the Resia Valley and in the Malga Coot cirque. Meanwhile the subsequent lowering of temperature conditions is able to cause a gradual increase of snow cover, especially in the orographic left, leading to a thickening and widening of the existing glaciers, therefore accelerating the flow and lowering the glacier tongues. Once all the smaller ice bodies tend to converge and form the main Resia Glacier, the system can be considered virtually completed with all the smaller fed glacial bodies acting as a unique system, flowing from East to West.

At this stage the persistence of this glacial system lives a delicate equilibrium where small changes in MAAT or MAP can lead to large variations in mass-balance, particularly evident in area with high precipitation. Also during present time, even if globally glacier mass balance has been shown to be closely related to summer temperatures (Ohmura et al., 1992, Hughes & Braithwaite, 2008), it was observed that the accumulation-type glaciers are mainly controlled by the winter balance (Nesje et al., 1995; 2000). More recently Colucci & Guglielmin (2014) found that the present small glaciers of the Julian Alps are mainly influenced by winter precipitation, instead of mean summer temperatures, owing to the peculiar climatological characteristics of the area.

9. CONCLUSIONS

The Resia Valley represents a key area for depicting the sedimentary evolution during the last glaciation in the eastern Southern Alps. The thick glacigenic successions allowed the reconstruction of the dynamics of the onset of the glaciation, which was characterised by the initial spread of the glaciers of the Canin-Toudule and the Barman with the infilling of the former valley with fluvioglacial deposits (i.e., CRT-A), and glaciolacustrine successions (i.e., ZAI-A and the downstream laminated lacustrine fines). The spread of the Resia Glacier covered these units, causing their over-consolidation. Laterally, the interaction of the base of the glacier with the sharp pre-glacial topography caused the formation of peculiar subglacial deposits, with big sub-angular boulders and glaciolacustrine fines (Stolvizza section). The Resia Glacier during the LGM reached the maximum thickness of ca. 550 m, joining the Fella Glacier at Resiutta. During the Late Glacial, at least two main stadials were recognised through the presence of frontal moraines and ice-dammed deposits. In the first, glacier streams flowed down the Resartico and Barman valleys, damming the trunk valley and causing the formation of lakes and the aggradation of the fluvioglacial deposits fed by the outwash streams from the glaciers of the upper valley. In the second stadial phase glaciers were confined in the upper accumulation areas, and only the Barman and Canin-Toudule ice streams reached the base of the slope, thanks to the climatological setting. The ELA calculation at 1188 m a.s.l. (AAR 0.4) for the Barman Glacier during the first Late Glacial phase is similar to the LGM ELA for the Julian Prealps. This low elevation points to the effect of debris cover and avalanching in decreasing the size of the accumulation area. In fact, the accumulation areas of the Resia catchment are located in one of the highest precipitation rate sector of the Alps (present MAP > 3000 mm). These climatological characteristics still allow the preservation of very small glaciers, glacierets and firn-patches even under the present, warmer climate, suggesting the locations and conditions that may have triggered (and will trigger) the onset and growing of new glacial areas.

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