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GLACIER DYNAMICS IN SAN GIACOMO VALLEY (CENTRAL ALPS, SONDRIO, ITALY)

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ABSTRACT: San Giacomo Valley is located in the Central Alps, and cross-cuts the alpine chain from N to S. Geologically, it is dominated by the Tambò and Suretta alpine nappes, which influence the valley morphology: its southern part has regular slopes, whereas its northern part shows flat topographies correponding to the thrust surfaces of the Tambò nappe.
Structural and geomorphological analysis highlighted the tectonic-structural origin of the valley. Although the alpine valleys network changed during orogenesis, the morphology of San Giacomo Valley was only little modified at least since the Miocene. The glacial erosion had negligible influence in shaping the valley forms. The large dimension of the glacial erosional morphologies in San Giacomo Valley can not be related with certainty to the last glaciation, but to glaciations in general, whereas small erosional morphologies and the depositional morphologies are most probably the result of the last glaciation.
The observations carried out on glacial morphologies and the sedimentological study of tills indicate that San Giacomo Valley, at the last glacial maximum, was the accumulation zone of San Giacomo glacier. From the trimline evidences, both the ice extension in the valley at the LGM and the longitudinal profile of the glacier were reconstructed. The valley at the glacial maximum hosted a single glacial tongue, with the exception of the Truzzo-Lendine glacier, which was suspended on the main glacier.
The relationship between the San Giacomo and the Engadina-Bregaglia glaciers is here also reconstructed. At the junction of the two glaciers, in Chiavenna Valley, the Engadina-Bregaglia glacier had higher elevation and larger mass than the San Giacomo glacier. South of San Giacomo Valley, in Chiavenna Valley and in what is today upper Lake of Como, the San Giacomo glacier was squeezed against the right valley slope, but then continued southward for some kilometers as a distinct glacier tongue. This inference is supported by the distribution of tills, which contain lithotypes sourced from the San Giacomo Valley. Only during advanced stages of melting the San Giacomo glacier tongue disappeared.
The morphologies of the glacial melting phases were here used to reconstruct the evolution of the glacier tongues of the main and lateral glaciers, as well as to reconstruct their relationships. Through the deglaciation, the accumulation zone gradually shrank and the ablation zone expanded, with contemporaneous upstream shifting. Through the deglaciation, lateral glaciers parted from the major glacier and expanded, reaching their maximum extensions during the retreat of the main valley glacier.
The recognizable retreat phases do not identify all the steps of glacial phases occurred, but only those whose sedimentological and morphological evidence has remained. The building of lateral moraines or the deposition of erratics occurred during minor glacial advances, which may have not had the same morphologic evidence throughout the valley.

Keywords: glacier dynamics; LGM; Central Alps; geomorphology; glacial reconstruction; glacial morphologies.

1. INTRODUCTION

In spite of some recent studies on the extent and timing of the last glaciation and deglaciation in the Alpine region (e.g., Kelly et al., 2004; Ivy-Ochs et al., 2006, 2008, 2009; Reitner, 2007; Starnberger et al., 2011; Darnault et al., 2012), field-based knowledge about glacier dynamics in high valleys is still fragmentary. In the perspective of filling this lack of knowledge and providing a comprehensive field study, we focused on San Giacomo Valley, which is an isolated alpine valley wide enough (~200 km^2) to be suitable for an accurate field survey. We mapped the valley landforms, and, in particular, the morphologic and sedimentological evidences connected to LGM glacier dynamics.

We did not obtain dates for the events highlighted by morphologies and sediments, but we used their geometry and their position to obtain a relative sequence of events (identified by glacial advance phases during the general melting). In this way we could reconstruct San Giacomo glacier dynamics in its final stages of melting.

The data collected in San Giacomo Valley (De Finis, 2012; Riganti, 2012; Taglieri, 2012; Tantardini, 2012) include trimline elevations, position of significant erratics, mapping of the extension and geometry of moraines. A first interpretation of these field data has permitted to identify glacial retreat phases of the major glacier and of its tributary glaciers: these have been summarised in a map of the glacial retreat phases. On the basis of the identification and correlation of glacial phases, two paleogeographic maps of ice extent at different times are presented.

2. GEOGRAPHIC AND GEOLOGIC OVERVIEW

Val San Giacomo (San Giacomo Valley is located in the Central Alps, and runs roughly N-S from Passo dello Spluga, to Chiavenna. South of Chiavenna, along the prosecution of San Giacomo Valley, lies Piano di

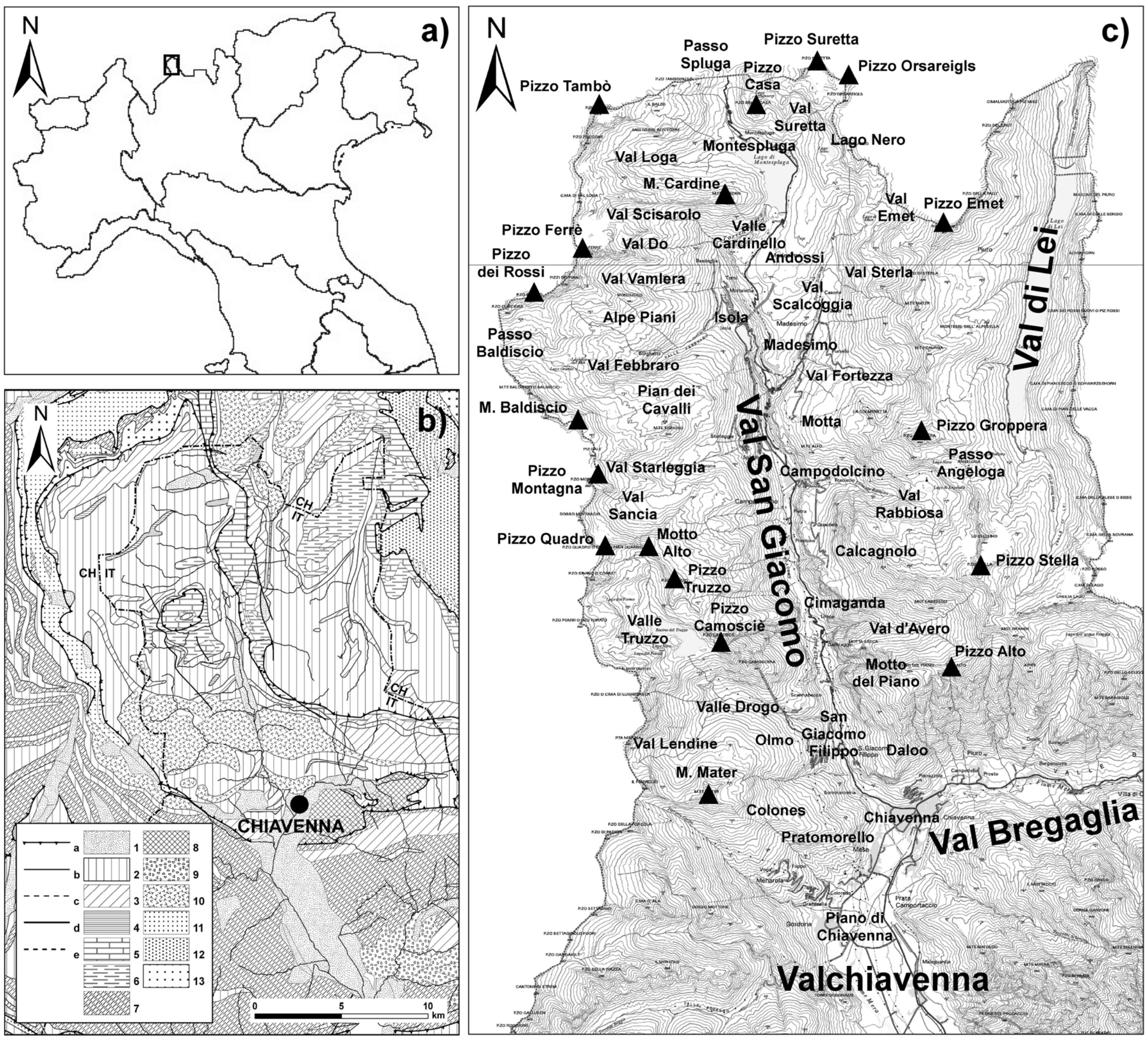

Fig. 1 - a) Position of study area in the Alps. b) Geologic map of the examined region. a – thrust, b – certain fault, c – uncertain fault, d – certain tectonic line, e – uncertain tectonic line, 1 – Quaternary deposits, 2 – paragneiss and mica schists, 3 – orthogneiss and mica schists, 4 – amphibolites, 5 – carbonatic metasedimentary cover, 6 – crystalline metasedimentary cover (mica schists, thin paragneiss, quartzites), 7 – orthogneiss, 8 – Chiavenna Ophiolites and rocks of oceanic domain, 9 – Masino-Bregaglia (Bergell) intrusion (granites, granodiorites, diorites), 10 – Truzzo intrusion (metagranites), 11 – Bündnerschiefer, 12 – Bündnerschiefer, Schams nappe, 13 – Bündnerschiefer, Avers nappe. Modified after the Geologic and tectonic chart of Switzerland 1:500 000. c) Overall map of study area. Toponyms here are the ones which the text refers to.

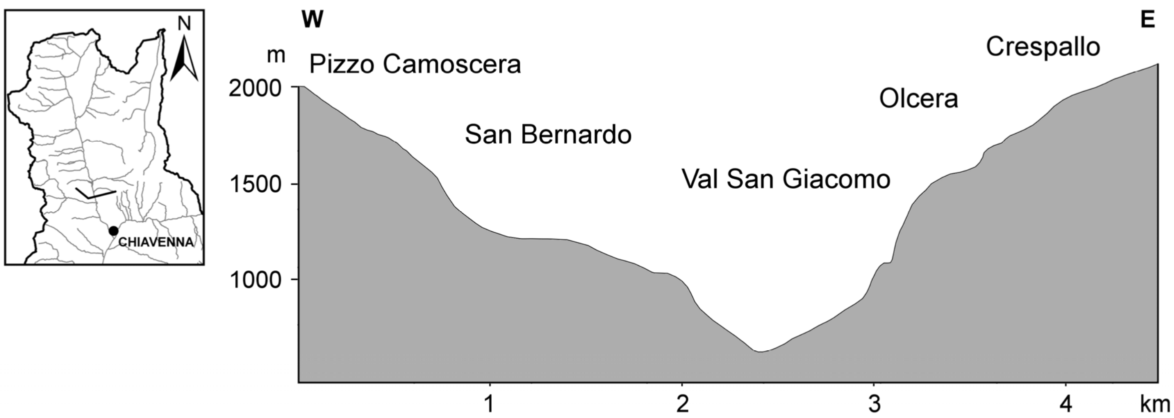

Fig. 2 - Schematic cross section of the southern San Giacomo Valley. The slope, constituted by the Truzzo Metagranite, presents a rounded morphology.

Fig. 3 - San Giacomo Valley seen from the southern slope of Mt. Cardine. It is possible to notice the change in morphology with respect to the southern portion of the valley. At altitudes between about 1800 and 2000 m the slope is much larger than in the valley bottom, and there are some large terraces on the thrust surface between Suretta and Tambò nappes (a – Motta; b – Andossi; c – Pian dei Cavalli).

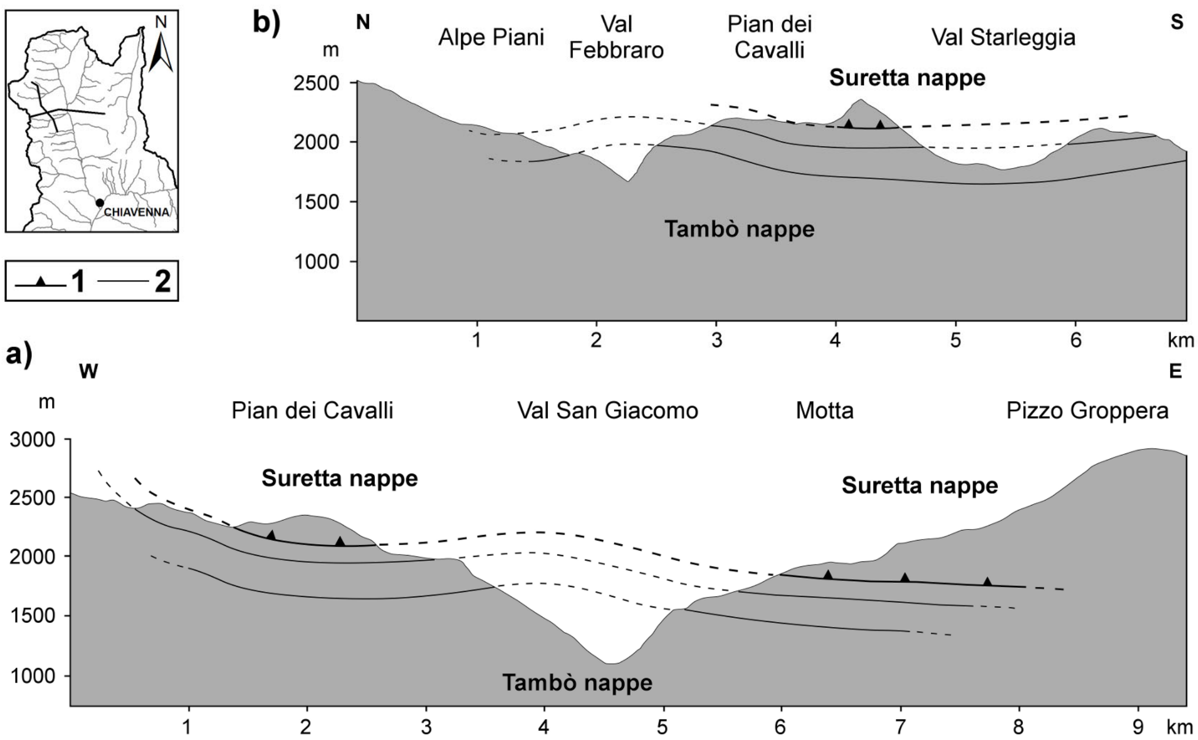

Fig. 4 - Schematic cross sections of the Pian dei Cavalli area. 1: Suretta-Tambò nappes thrust; 2: inverse fault surface parallel to thrust surface. The cross sections shows how the topography is in many areas parallel or sub–parallel to the surfaces of inverse faults, representing, from a geomorphological point of view, structural sub-horizontal terraces and uplands. The difference between the upper valley slopes and the lower, more incised ones, is evident in section a).

Fig. 5 - Panoramic view of Pian dei Cavalli. The photo is taken from the northern area of Pian dei Cavalli towards South. Mount Tignoso (in the center) is constituted by the rocks of Suretta nappe, whereas Pian dei Cavalli is constituted by the carbonatic rocks of the Tambò nappe cover. The thrust surface passes a few meters above the Pian dei Cavalli topography, hidden by the large rock glacier at the toe of Mount Tignoso. To the West the thrust folds upwards and crops out in the saddle between Mount Tignoso and the large carbonatic cuesta, the surface of which is practically coincident with the thrust surface. Despite the distortion provoked by the panoramic view and the presence of till, it is evident that Pian dei Cavalli topography is parallel to the Suretta-Tambò thrust surface: to the East, the plain topography of Pian dei Cavalli is almost horizontal, while to the West it curves upwards as the thrust surface does on the carbonatic cuesta.

Chiavenna, generally known as Valchiavenna (Chiavenna Valley), which is wider than San Giacomo Valley. To the South, Chiavenna Valley forms a junction with Valtellina and Upper Lake Como. Upstream, the valley is oriented East-West and is named Val Bregaglia (Bregaglia Valley) (Fig. 1).

Chiavenna Valley is located north of the Insubric Line (Periadriatic Lineament) which runs East-West along Valtellina. In Chiavenna Valley, Adula, Tambò and Suretta penninic nappes crop out, which consist of a crystalline pre-permian basement, lithologically composed of micaschists, paragneiss and metagranitoids. Within the Tambò nappe basement the Truzzo Metagranite is intruded. This is a late-variscan pluton, subsequently deformed by the Alpine orogeny, which crops out in an East - West belt and which transversely crosses San Giacomo Valley and continues in Bregaglia Valley.

Nappes are separated from permo-mesozoic metasedimentary covers, composed by metapelites and carbonates. In particular, within the metasedimentary cover of Tambò nappe are Spluga Quartzites, which lie immediately beneath the other cited rocks and have been interpreted either as a part of the crystalline basement or as a metamorphosed permian riolitic sequence (Sciesa, 1991).

In San Giacomo Valley the nappes have a nearly tabular geometry and overlap each other in a regular way, with a general low dip towards East-Northeast, whereas in southern Chiavenna Valley the same units are folded and tilted.

2.1. Morphology of the valley

The morphology of the southern part of San Giacomo Valley is closely connected to the presence of Truzzo Metagranite. The valley is narrow, with steep slopes, characterized by rounded outcrops (Fig. 2) because of the curve fractures present in the metagranite (Cloos, 1925; Migòn, 2006). The morphology dramatically changes northwards (Fig. 3): the valley becomes larger in the higher slopes, where there are also large flat surfaces (such as Andossi and Pian dei Cavalli), whilst it remains narrow and more incised in the lower slopes (Fig. 4, Fig. 5). On some of these surfaces (Andossi, Pian dei Cavalli, Motta) the metasedimentary carbonatic covers crop out (Fig. 5), so these surfaces correspond to the thrust surface of Suretta nappe on Tambò nappe. The other surfaces also correspond to structural surfaces parallel to the thrust surface. San Giacomo Valley itself, starting from the end of Cardinello Valley, is a structural valley formed along a strike-slip fault.

San Giacomo Valley, as demonstrated by studies on perialpine sediments and on the structural evolution of the Central Alps (Bernoulli et al., 1993; Bersezio et al., 1993; Brugel et al., 2000; Carrapa & Di Giulio, 2001; Gelati et al., 1991; Giger & Hurford, 1989; Hansmann, 1996; Kuhlemann, 2007; Kuhlemann & Kempf, 2002; Sciunnach et al., 2004; Schlunegger et al., 1998; Schmid et al., 1996; Spiegel et al., 2001), already existed during the Miocene and, probably, it had gained the present morphology already in the Upper Miocene and during the Messinian salinity crisis, as it is a tributary valley of Lake Como Valley which deepened during the Messinian, like most Southalpine valleys (Biella et al., 2001; Bini, 1994; Bini et al., 1978; Brambilla & Lualdi 1986; Cita et al., 1990; Cita & Corselli, 1990; Cita & Corselli 1993; Corselli et al., 1985; Felber et al., 1991; Felber et al., 1994; Felber & Bini, 1997; Finchk, 1978; Finchk et al.,1984; Lualdi, 1981; Quattrone et al., 1990; Rizzini & Dondi, 1978; Rutishauer, 1986). Therefore, glacial erosion is not the only cause of the morphology of San Giacomo Valley: weathering, denudation, slope dynamics and fluvial erosion have had greater importance in its formation.

Given that both glacial geometry and dynamics are influenced by land topography, it is useful to briefly describe the valley. Loga Valley, which can be considered as the upper part of San Giacomo Valley, is directed W-E and is wide, with a gently dipping valley bottom smoothly connected to the area of Lake Montespluga, which is one of the flat structural surfaces existing at the contact between Suretta and Tambò nappes. The flat area extends southwards in continuity with Andossi area. A NE-SW fault, corresponding to the Cardinello valley, causes the deviation of the valley axis and its fast deepening; the difference in height between Lake Montespluga and the valley bottom north of Isola is about 600 m. The area of Isola becomes a large, elongated depression surrounded by high and steep-sloped reliefs. From here up to Piano di Chiavenna the valley is perfectly straight.

The flat, structural area of Montespluga - Andossi continues southwards forming the terraces of Motta, although separated from these terraces by Scalcoggia valley, and, towards SW on the other side of the valley, forms Piano dei Cavalli.

Some deeply incised lateral valleys connect to San Giacomo Valley bottom: Febbraro Valley, Avero Valley and Drogo Valley. These are structural valleys due to faults or to lateral contact with the intrusive body of Truzzo Metagranite. Other valleys remain suspended on San Giacomo Valley, completely as Sancia Valley, or partially as Rabbiosa and Groppera valleys. These valleys end in more or less extended flat areas lying on structural surfaces which are at the contact between Tambò and Suretta nappes (Groppera Valley) or surfaces parallel to this (Sancia, Rabbiosa Valley).

At the junction with Chiavenna Valley, San Giacomo Valley deviates towards SE following the edge of the Truzzo Metagranite intrusion. At this diversion, on the right slope of the valley, a NW-SE ridge departs from Mount Mater and obstructs the right part of the valley. This ridge comes down from Colones (1700 m a.s.l.) to Pratomorello (1100 m altitude.s.l.), on a distance of 2,5 km, with a low gradient in the upper slope and then with a much more pronounced gradient near the valley bottom.

3. GLACIAL MORPHOLOGY

During the Pleistocene, in the last 2,6 millions years, the upper Lombardy plain and the terminal parts of alpine valleys were interested at least by thirteen glaciations (Bini, 1996; Bini, 1997)[1]. As the term "glaciation" is ambiguous, the definition of glaciation adopted here follows Bini (1997): "The term "glaciation" is applied here to a specific glacial advance and recession, the deposits of which are separable from those of other glaciations by evidence of extensive recession and downwasting of glaciers, or by evidence of warm climate as interpreted from pollen diagrams or weathering profiles. The terms "warm" and "cold" are used here in a very general sense to indicate broad differences in the climate of intervals separating glaciations (Richmond, 1986)". The identification and the concept itself of a glaciation is therefore related to the observation of sediments and it follows that the number of glaciations can vary from an area to another, from mountain to upper plain, from the north slope of a ridge to the south slope, etc.

As a consequence, even if in the prealpine morenic amphitheatres thirteen glaciations were recognized, it is possible that in the mountains, as in San Giacomo Valley, the situation was different. Richmond & Fullerton (1986), in fact, recognize various glaciations dated with chronometric methods during Lower Pleistocene and limited to mountainous areas (Alaska, Sierra Nevada, Wyoming, Cascade Mountains). If in North America there were glaciations in a period of time previously considered to be lacking great glaciations, such a situation is likely to have recurred in the Alps too[2], even if the absence of sedimentary evidence only permits to formulate hypothesis. So, in San Giacomo Valley it is reasonable to suppose that glaciations were more than thirteen (Bini & Pellegrini, 1998).

In the internal alpine valleys, as in San Giacomo Valley, it is not possible to recognize the various glaciations, because the denudation and the erosion on slopes are very intense and so, apart from rare cases, older deposits were not preserved. Only four outcrops of older-than-LGM glacial deposits are known in the whole Valtellina (Bini et al., in press; Montrasio et al., 2012), whereas in San Giacomo Valley pre-LGM glacial deposits are absent.

It is thus possible to recognize the sediments related only to the last glacial expansion (Cantù Glaciation, corresponding to the LGM) (Bini, 1996; Bini, 1997), well distinguishable thanks to the thin surface weathering horizon, less than one meter thick.

Moreover, in this region, all the glaciations had more or less the same extent and therefore their trimline must be comprised in a few tens of meters of altitude (Ballantyne, 1997; Benn & Evans, 1998; Bini, 1996; Bini et al., 2009; Kelly et al., 2004).

3.1. Erosional morphologies

All morphologies caused by glacial erosion are often ascribed to the last glaciation, for example some valley entrenchments of some hundreds of meters (Perello et al., 2011). As the recognized glaciations related to Adda Glacier are thirteen, and there are no reasons to suppose that the last glaciation had a more important erosional behaviour than the former ones (the glaciers had a similar mass in all the glaciations; see references above), it is necessary to think that the currently observable morphologies result from the sum of the effects of all glaciations: in fact, if all the glaciations eroded a thickness similar to the one attributed to the last glaciation, the total thickness of eroded material would be enormous, and equal to thousands or even tens of thousands of meters in a portion of alpine chain which is about 2500 - 3000 m high. The development of San Giacomo Valley in its present-day morphology precedes all glaciations, as documented by studies on perialpine sediments and by the structural evolution of the Central Alps (see references above). The valley shows little evidence of large glacial erosional morphologies which, as a consequence, are unlikely to be related exclusively to the LGM, but to glaciations in general.

On the contrary, morphologies with smaller dimensions can be ascribed to the last glaciation (Bini et al., 2009), because it can be assumed that during interglacials weathering cancelled older morphologies. We observed glacial striae and ice-scoured rocks that act as ice flow indicators. Obviously, glacial striae indicate flow directions coincident with valley directions; in some cases, however, due to a more flat topography, striae allow to determine the presence and the flow of the local glacier or of the valley glacier, like at Alpe Zocana, in the eastern part of Pian dei Cavalli, where glacial striae show an ice flow with an azimut of 175° (Riganti, 2012), not compatible with the directions of flow of all the local glaciers that could have occupied the area, but only with San Giacomo glacier.

1 At present day, the "classic model" introduced by Penk e Bruckner (1909) based on four glaciations is no more valid (Bowen, 1978; Šibrava et al., 1986; Bini, 1997): the objective data of the previously published works remain valid, but the interpretations do not.

2 In Lombardy context a great glaciation is a glaciation, whose evidence is based on sediments, during which glaciers reach the upper plain.

Fig. 6 - Gentle till at Andossi. The photo is taken from the northeastern tip of Andossi, towards SW. West of Andossi, on the right side of the photo, there is Cardinello Valley; East of Andossi there is Scalcoggia Valley. The junction between the two valleys is the Isola depression, SW of Andossi (center of the photo). During the LGM and the first stages of melting San Giacomo glacier flowed over this area toward SSW. By phase San Giacomo 65, the glacier became too thin to flow over Andossi. So, an area of dead ice formed: the gentle till with scattered erratics was deposed at its complete melting. During advanced stages of melting the glaciers did not reach Andossi, which was free from ice: and two glacial tongues flowed separately in Cardinello Valley (towards SW) and in Scalcoggia Valley (towards SSW).

Fig. 7 - Drumlin at Andossi. The photo is taken from S towards N. The drumlin testifies an ice flow directed from NNE to SSW. The drumlin (250 m long, 20 m large, up to 7 m high) is covered by thin glacial deposits (ablation till). In this flat topography area of Andossi there are also some fluted moraines, oriented in the same direction.

3.2. Depositional morphologies

Even if widespread, glacial deposits in San Giacomo Valley are thin (usually a few meters thick), except for some particular areas like in Starleggia-Sancia valleys between 1750 - 1800 m of altitude or on the eastern slope of Mount Mater. Most deposits and the associated morphologies are related to the retreat phases of glaciers.

With respect to evidences for the maximum expansion of San Giacomo glacier, there are lateral moraines only in the southern part of the valley in Drogo Valley (two short moraines). In the rest of the valley, moraines are absent, and only subglacial morphologies like cover moraines and till plains (at Andossi, Pian dei Cavalli, Motta) (Fig. 6), subglacial hills (at Andossi, Pian dei Cavalli, Loga Valley, Lendine Valley), and drumlins (at Andossi and Lendine Valley) (Fig. 7) were observed. Part of these morphologies (the ones located in Andossi, Lendine Valley) could be linked to retreat phases of the glacier.

Lateral morphologies related to ice flow are absent even in areas with a flat topography favourable to the conservation of glacial morphologies, like at Piano dei Cavalli, where only scattered, thin till covers (mainly less than a meter thick) and boulders crop out. This implies that San Giacomo glacier was not covered by debris. This fact, along with the position of the valley in the Alps and its configuration, suggests that San Giacomo glacier was in the accumulation zone and not in ablation zone almost as far as Drogo Valley.

Fig. 8 - Extension of glaciated area in San Giacomo Valley at the LGM. 1 – glaciated area; 2 – upper border of the glaciated area (trimline). The reconstruction was based upon trimline data (Table 1) and assumed an analogy in behaviour with present glaciers.

Morphologies related to retreat phases of San Giacomo glacier are more widespread: lateral moraines where the topography allows for their preservation (Montespluga, Andossi, Motta, Mount Mater), erratics and hummocky moraines (Drogo, Starleggia, Sancia and Truzzo valleys, Lake Montespluga).

Minor glaciers, merging with the San Giacomo glacier, could advance downstream only when the main glacier was retreating and was no longer blocking their flow. In lateral valleys (Scisarolo Valley, Do Valley, Starleggia-Sancia valleys, Suretta Valley, Lake Emet Valley, Angeloga Valley) we observed many moraines deposited during these phases which, in some cases, reached low elevations.

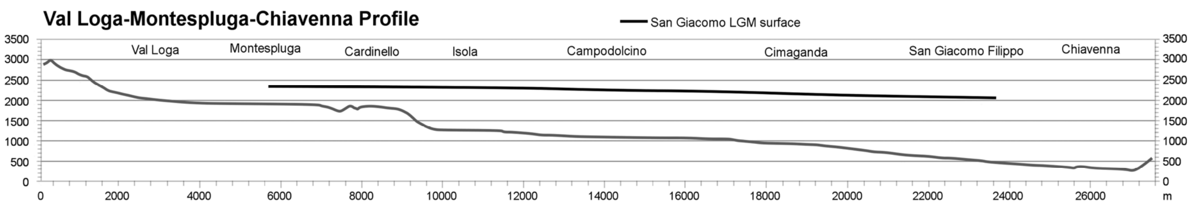

Fig. 9 - Topographic profile of San Giacomo Valley and reconstructed surface of San Giacomo ice mass (altitudes of the trimline).

	Altitude	Place	Glacier	Coordinates (UTM zone 32 N - WGS 84)		Evidence
TL001	2320	Monte Cardine	S. Giacomo	525681	5146743	Slope rupture, modelled bedrock below trimline.
TL002	2153	Pizzo Camosciè, E slope	S. Giacomo	525353	5134928	Lateral moraine.
TL003*	2950	Pizzo dei Rossi	Piani-Bianco	520170	5144051	Modelled bedrock below trimline.
TL004*	2460	Monte Baldiscio	Bianco	519717	5142150	Modelled bedrock below trimline.
TL005*	2400	Pizzo Montagna	Quadro-Starleggia	522253	5138672	Slope rupture, less rough rock below trimline.
TL006	2213	Motto Alto, E slope	S. Giacomo	524121	5138201	Little slope rupture, sharp reduction of till volume.
TL007	2058	Monte Mater, E slope	S. Giacomo	525700	5130656	Maximum altitude of till sedimentation on a ridge reachable only by the principal glacier. Lithology of till clasts different from bedrock lithology.
TL008*	2310	Pizzo Camosciè, W slope	Truzzo	524754	5134689	Modelled bedrock below trimline.
TL009	2320	Pizzo della Casa (Pizzo Suretta, W slope)	S. Giacomo	526173	5149123	Slope rupture, ice-scoured rocks.
TL010	2330	Alpe Spluga (Pizzo Suretta, SW slope)	S. Giacomo	526925	5149002	Slope rupture, ice-scoured rocks.
TL011	2310	Lago Nero	S. Giacomo	528068	5147654	Slope rupture.
TL012*	2320	Lago d'Emet	Emet, Spadolazzo	529036	5147372	Slope rupture, ice-scoured rocks.
TL013	2310	Valle Sterla	S. Giacomo	529237	5144311	Slope rupture, smoother topography below trimline.
TL014	2220	Valle Fortezza	S. Giacomo	529034	5140280	Slope rupture.
TL015	2080	Motto del Piano	S. Giacomo	530136	5133385	Maximum altitude of till sedimentation on the slope, erratic of Spluga Quartzite.

Tab. 1 - Trimline data identified in San Giacomo Valley. The asterisk after the identification code indicates a datum not related to the major glacier but related to one of minor glaciers.

4. TRIMLINE AND GLACIERS GEOMETRY DURING THE MAXIMUM EXPANSION

In literature we can find various methods to identify the trimline. Some authors (for example: Florineth & Schlüchter, 1998; Kelly et al., 2004) set the trimline at the upper limit of erosional morphologies on bedrock. Other authors (for example Ballantyne et al., 1998) indicated that the trimline coincides with the upper limit of removal of weathered bedrock or debris by glaciers. To identify the trimline, Kelly et al. (2004) used till and erratics (whereas Van der Beek & Bourbon (2008) relied on drumlin and lateral moraines. The trimline also coincides with the line which separates bedrock deeply eroded by the glacier from not eroded bedrock and therefore deeply weathered by frost and by chemical and biological weathering (Ballantyne et al., 1998; Ballantyne et al., 2008). At the trimline a convex or concave slope rupture can often be observed, depending on bedrock geomechanical properties (Florineth & Schluchter, 1998).

In this study we did not privilege a particular criterion, but we tried to identify the approximated or real trimline in all feasible ways.

Table 1 reports the data relative to the trimline found in San Giacomo Valley.

All the trimline evidences can be related to the LGM: those in till thanks to the characteristics of their weathering profile (the most common soils in San Giacomo Valley are leptisols and thin cambisols with Munsell Soil Color Chart hue 10YR (Comolli et al., 2011), and those identified thanks to erosional morphologies because the trimline evidences based on morphologies of bigger dimensions have the same altitudes as in previous glaciations (whereas smaller dimension morphologies previous to the LGM have been erased and, thus, the observable morphologies are related to the LGM).

From these field data, a map of the maximum expansion of glaciers in San Giacomo Valley was drawn (Fig. 8). The whole valley was occupied by ice and only the highest peaks and ridges were ice-free. Only in the final southern part of the valley, we could find wide ice-free slope areas, and in this sector the ablation zone of San Giacomo glacier likely began, the evidence being the presence of lateral moraines.

The major glacier trimline altitudes (Tab. 1) projected onto the valley axis allow us to obtain a surface profile of San Giacomo glacier (Fig. 9) which is not the real glacier surface, but a reconstruction of the locus along the glacier's axis with altitudes which equal the altitude of trimline.

Between the northern and the southern evidences of the trimline, San Giacomo glacier decreased in altitudes of about 272 m along a distance of ca. 18 km, with an average slope of 0,9°. The glacier thickness between the valley bottom and the trimline, by assuming an adequate thickness (20-30 meters maximum) for the sediments in the valley bottom, was 450 m at Lake Montespluga (TL010), 600 m at Mount Cardinello (TL001), 1100 m at Lake Isola, 1150 m at Campodolcino, 1230 m at Cimaganda (TL002) and 1550 m at San Giacomo Filippo (TL007). The ice mass thickness, therefore, increased downstream.

Between Lake Montespluga and Lake Isola, along a distance of 2,8 km, ice thickness increased from 450 m

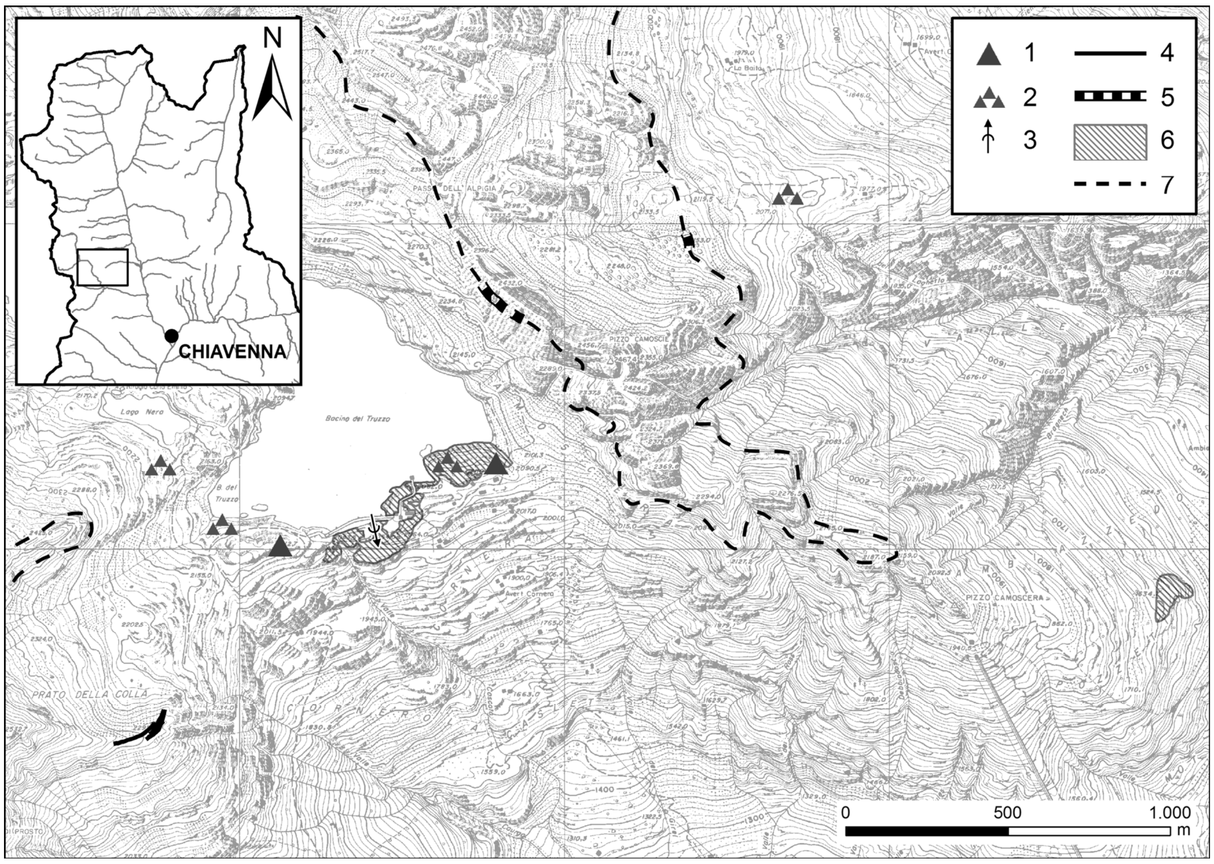

Fig. 10 - Position of San Giacomo glacier (TL002, Table 1) and Truzzo glacier (TL008, Table 1), and trimlines on the ridge between Pizzo Truzzo and Pizzo Camosciè. Truzzo glacier is kept suspended over the major glacier by the morphologic step in the Truzzo granitic intrusion (Fig. 1). The dam area, where the suspended valley ends, suggests the presence of seracs (and of the consequent increase in ice flow velocity) because of the strong scouring of the bedrock and because of the presence (the only case in the valley) of glacial striae. Legend: 1) significant erratic; 2) scattered erratics; 3) glacial exaration striae; 4) moraine crest; 5) trimline; 6) ice scoured rock; 7) reconstructed limit of glaciated area.

to 1100 m because of a morphologic step along the valley bottom, whereas south of Lake Isola the increase in thickness was more gradual.

San Giacomo glacier, belonging to the Adda and Po hydrographic basins, came into contact at various points with glaciers in adjacent valleys belonging to Rhine hydrographic basin, like at Passo dello Spluga, in Suretta Valley, in Lake Emet Valley, in Angeloga Valley and in Febbraro Valley.

From the point of view of ice volume, the most important lateral glacier was Truzzo glacier which, during the maximum expansion, joined Lendine glacier. During its maximum expansion the whole Truzzo Valley acted as the accumulation zone of Truzzo glacier. In the southern part of Truzzo basin the trimline was at 2310 m a.s.l. (TL008), whereas, on the other side of the same crest (Fig. 10) San Giacomo glacier had a trimline at 2153 m a.s.l. (TL002). As a consequence, because of the morphologic step (Fig. 11), the Truzzo glacier had to form an ice fall to join San Giacomo glacier which was filling Drogo Valley. All the other glaciers are located in northern areas, within the accumulation zone which they are part of and, therefore, they are in direct continuity with San Giacomo glacier. The areas not surmounted by glaciers were the watershed crests. Mount Cardine crest and, in the middle of the valley, Pizzo Truzzo and Calcagnolo crests were also free from ice. Furthermore, there were a series of little isolated nunataks (Fig. 8).

5. RELATIONSHIPS BETWEEN SAN GIACOMO GLACIER AND ENGADINA-BREGAGLIA GLACIER

San Giacomo and Engadina-Bregaglia glaciers joined in the area of Chiavenna, and formed a single glacier which flowed southwards until it joined Valtellina (Adda) glacier.

According to Florineth (1998) and Bini et al. (2009) the Engadina-Bregaglia glacier formed a glacial dome, located in the area of St. Moritz, which reached ca. 3000 m of elevation, with thicknesses of about 1200 m. From this dome towards Bregaglia Valley, the glacier lowered in altitude down to 2250 m at the trimline located at Villa di Chiavenna (6 km east of Chiavenna) (Stevenazzi, 2010). At the morphologic step of Maloja Pass the glacier formed a ca. 200-m-high ice fall. The glacier slope west of Maloja Pass is lower than east of the pass (Florineth, 1998; Stevenazzi, 2010), and is approximately 0,7°.

At present there is no evidence of the Engadina-

Fig. 11 - Drogo Valley seen from East (Daloo) towards West. On the left slope of the valley there is a morphologic step at the junction with Truzzo Valley. At the LGM, Truzzo glacier flowed from its valley over this step towards San Giacomo glacier which filled Drogo Valley. San Giacomo glacier trimline was, in this area, ca. 250 m lower than the Truzzo glacier trimline (Fig. 10), so the latter glacier formed an ice fall over the morphologic step.

Bregaglia glacier trimline on the slope north of Chiavenna or on the south-east one, while in the southern part of San Giacomo glacier, a little upstream of the contact with Engadina-Bregaglia glacier, the glacier trimline is observed at 2058 m (TL007) and 2080 m (TL015) of altitude. Because of this, the relationships between the two glaciers can only be hypothesized: by prolonging downstream the trimline of the two glaciers and assuming a constant gradient that is equal to the one in upstream areas, it is possible to calculate the expected altitude above Chiavenna. This altitude is 2020 m for San Giacomo glacier and 2170 m for Engadina-Bregaglia glacier; the Engadina-Bregaglia glacier surface would have been about 150 m higher than San Giacomo glacier surface (Fig. 12).

At the identified trimlines, Engadina-Bregaglia glacier had a volume that was about one fourth bigger than that of San Giacomo glacier. South of Chiavenna the widening of the valley with respect to northern areas must have caused a lowering in the altitude of the glacier's surface.

San Giacomo glacier was therefore smaller than Engadina-Bregaglia and flowed into Chiavenna Valley with a minor thickness and a lower volume. Nevertheless, even if the San Giacomo was squeezed and stretched by the major glacier along the western slope of Chiavenna Valley, it was not completely blocked inside its valley, but it flowed together with Engadina-Bregaglia glacier at least for a certain distance. In fact, at Mount Berlinghera (Fig. 13), located between the southern Chiavenna Valley and the northern end of Lake Como, approximately 13 km South of Chiavenna, Maggi (1992) found evidence of the presence of San Giacomo glacier.

The lithologic analysis of clasts in tills and erratics allowed recognition of two areas of distribution of clasts lithologies (Maggi, 1992):

- from the LGM trimline (1685 m above sea level) down to about 800 m of altitude the marker lithotypes are Truzzo Metagranite (from San Giacomo Valley and/or Bregaglia Valley) and Spluga Quartzites (exclusively from San Giacomo Valley);
- between 800 and 700 m of altitude Spluga Quartzites are less common than Truzzo Metagranite, hence sediment coming from San Giacomo Valley diminishes while the material coming from Bregaglia Valley increases.

Masino Valley Granodiorite, from Valtellina, has been found only 8 km downstream of Mount Berlinghera, in the area of Sasso Pelo, at 431 m of altitude as an erratic, and in tills below 400 m a.s.l..

So, during LGM, San Giacomo glacier, in spite of the presence of the SE crest of Mount Mater (Colones) which hindered its flow, was a distinct glacial body flowing to the northern tip of Lake Como. The sharp cessation in the supply of Spluga Quartzites sediment implies a change in glacier dynamics. Apparently, during melting, San Giacomo glacier (which had a smaller accumulation zone than Engadina-Bregaglia: this latter is 2,5 times greater than San Giacomo Valley, considering Bregaglia and Engadine valley til St. Moritz; Florineth, 1998; Bini et al., 2009), progressively decreased its mass with respect to the Engadina-Bregaglia glacier, until it disappeared as a distinct glacier just South of Chiavenna, with consequent dispersal of Spluga Quartzites in a greater glacial mass and their mixing within the other transported sediments.

6. GEOMETRY OF GLACIERS DURING RETREAT

The reconstruction of glaciers retreat phases was based on the position and the morphology of moraines and on the position of significant erratics, that is the erratics which remained in their original depositional position at glacier margin, by accounting for the geometry of the glacier and the present-day behaviour of major glaciers (Ballantyne et al., 1998; Ballantyne et al., 2008; Bini et al., 2009; Kelly et al., 2004; Florineth & Schlüchter, 1998).

During the maximum glacial expansion, lateral glacial tongues could have been blocked within their own valleys by the mass of the major glacier tongue (Bini, 1999), as it can be observed even in present-day glaciers. This is the case of San Giacomo Valley. During melting, the glaciers' mass balance was negative, but while the major glacier lost volume and moved upstream retreating from lateral valleys, the lateral glaciers advanced because they were not anymore blocked by the major glacier, which acted as a dam (Bini, 1999). The smaller glaciers could therefore deposit moraines and erratics on slopes in areas previously occupied by the major glacier and at lower altitudes than its lateral moraines. Even in this case there are several examples of this dynamics in present glaciers. The advance of lateral glaciers into the major valley is temporary and of short duration: then, they retreat (Bini, 1999).

In San Giacomo Valley, by considering the valley topography, moraines are not so common, and, when present, they are not very long and are not distributed in an homogeneous way, but they are concentrated in areas or slope zones. So the retreat phases can be reconstructed and correlatable only in limited areas, whereas among different areas they are correlatable in a more difficult way (groups of stand-alone glacial phases come out). Each phase was identified with an alphanumeric identification number starting from the most recent evidence (Fig. 14).

6.1. San Giacomo glacier

As the major glacier retreated, the accumulation zone of the glacier moved northwards, and the glacier began to feel more and more the effect of the topography of the valley and of the slopes; minor glaciers in lateral valleys began to move downstream towards San Giacomo Valley valley bottom.

At Colones, where the south-eastern ridge of Mount Mater is extended transversely to the ice flow, during the maximum expansion the glacier was thick enough to overstep the crest and flow southwards (there are about 330 m of difference in height between the trimline and the crest). As the glacier was losing thickness during the retreat, the presence of the crest confined more and more the glacier flow until phase Colones 31 (see Fig. 14) when the ice mass was blocked by the crest, and was forced

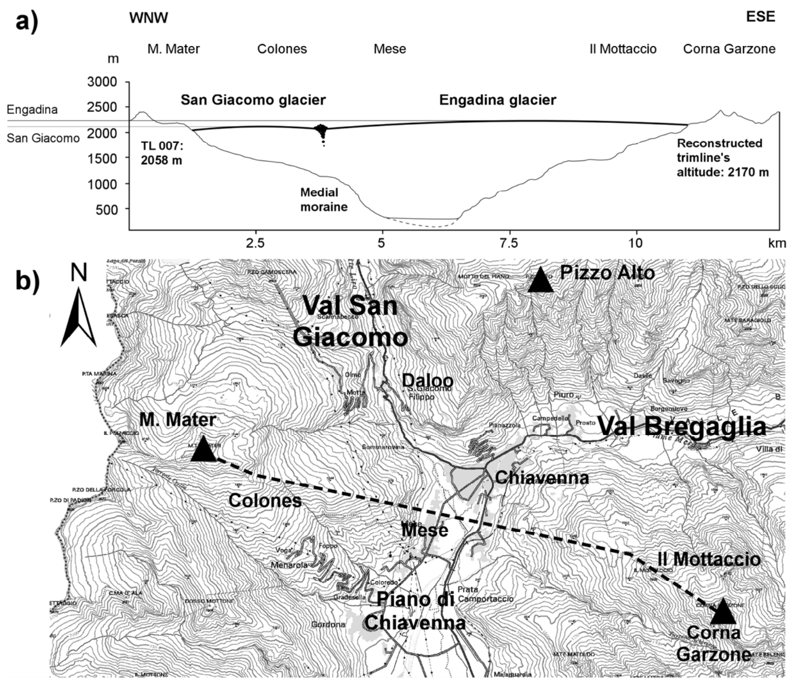

Fig. 12 - a) Schematic reconstruction of the relationship between LGM San Giacomo and Engadina-Bregaglia glaciers. San Giacomo glacier was, at trimline, about 160 m lower than Engadina–Bregaglia glacier, and forced on the right slope of Chiavenna Valley, while the majority of the available volume was occupied by Engadina-Bregaglia's glacial mass. The medial moraine was drawn on the basis of the behaviour of present glaciers (modified after Taglieri, 2012). b) Map of the area crossed by section a) (dashed line).

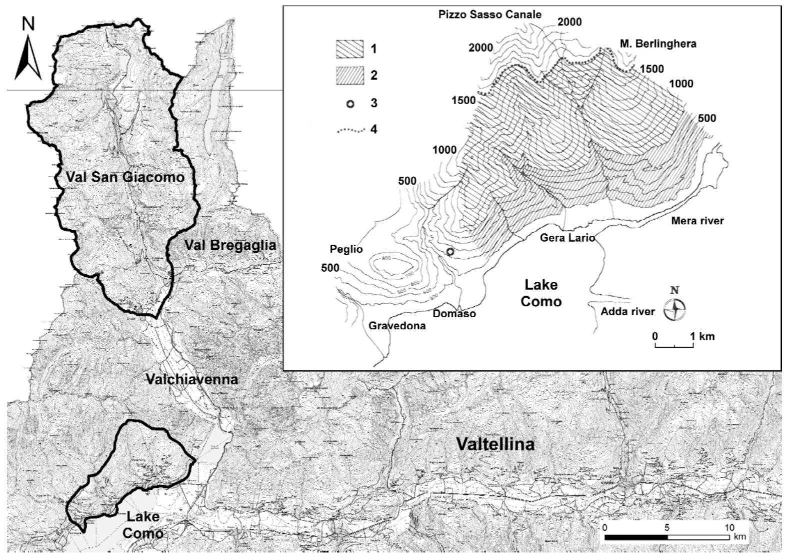

Fig. 13 - Position of the area described in Maggi (1992): the area is situated at the confluence between Chiavenna (coming from North) and Valtellina (from East) valleys, on a slope placed in front of the Adda glacier tongue which came from Valtellina and in a lateral position in respect to Engadina-Bregaglia glacier. The tills that can be found in this area allow reconstructing the dynamics between the two valley glaciers. Distribution areas of marker lithologies: 1) Truzzo Metagranite and Spluga Quartzite; 2) only Truzzo Metagranite; 3) erratic boulder contituted by Masino–Bregaglia intrusive rocks; 4) maximum extent reached by ice in the last glaciation (modified after Maggi, 1992).

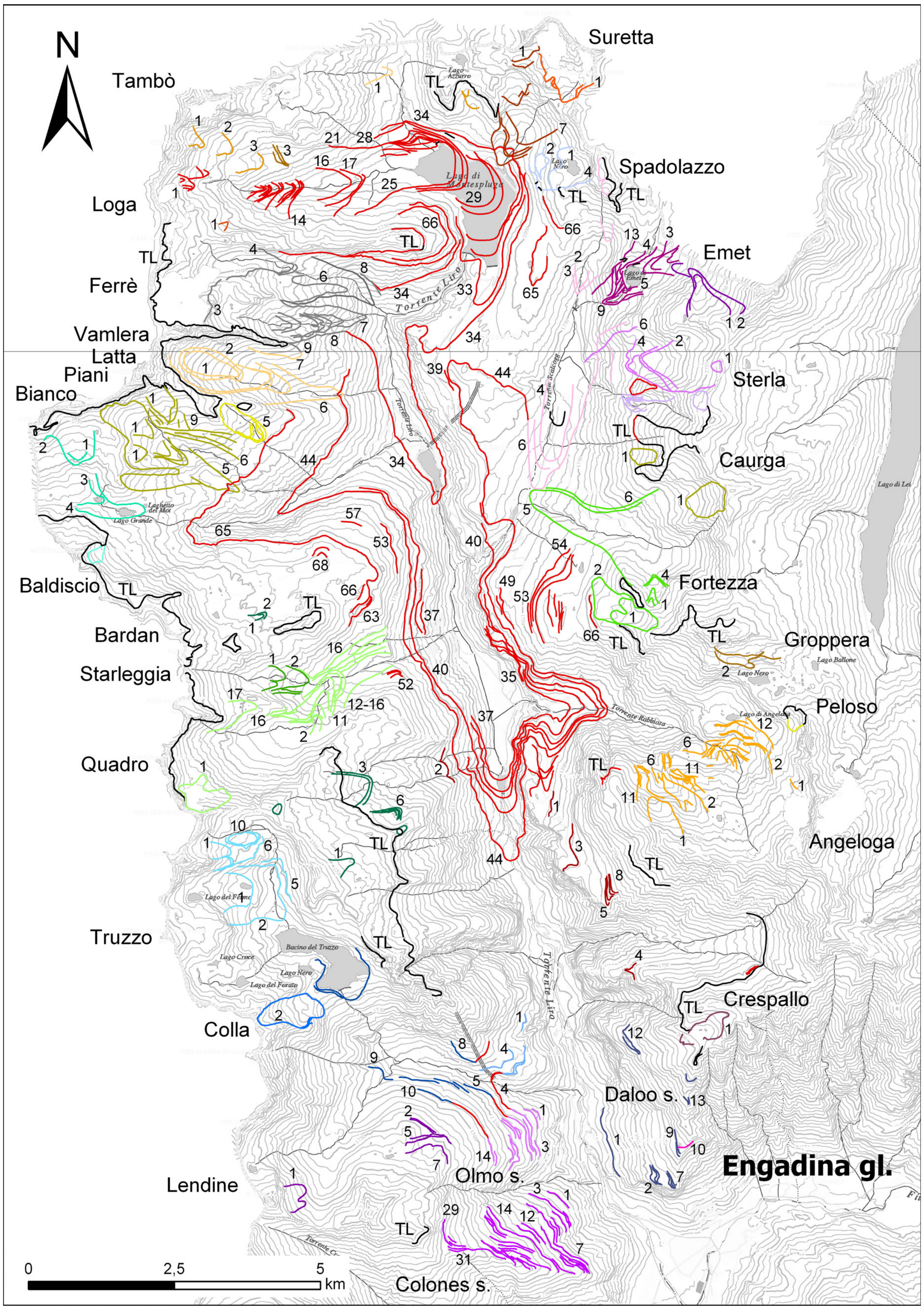

Fig. 14 - Map of glacial phases that were reconstructed in San Giacomo Valley. The numbering identifies the phase of the glacier, with smaller numbers for more recent phases and greater numbers for older phases. A different way of numbering (greater numbers toward greater altitudes) was used for the phases in glacial series Daloo, Olmo and Colones, because of the impossibility to correlate them with glacial phases more to the north.

Fig. 15 - Panoramic view of the area of Daloo. The photo is taken from NNE towards SSW. San Giacomo glacier flowed into Chiavenna valley (top center of the photo) from N (bottom-right corner of the photo), while Engadina-Bregaglia glacier came from E (left side of the photo). a – San Giacomo glacier moraine (phase Daloo 8). b – San Giacomo glacier moraine (phase Daloo 9), lying from N toward S. c – moraine deposited by the Engadina–Bregaglia glacier (Phase Daloo 10), oriented from E to W, highlighted by some little till hills near the lake and by the presence of erratics along its crest. It is evident the perpendicularity between moraine b and moraine c (deposited by glaciers flowing in different valleys) and the erosion of the western tip of the Engadina-Bregaglia moraine carried out by the phase Daloo 9 moraine.

to deviate its flow towards ESE. This configuration remained until phase Colones 7; in the following phases the glacier, thanks to different slope topography, flowed towards SE.

On the opposite slope of the valley, at 1350 m of altitude (see Fig. 14), we observed a moraine belonging to Engadina-Bregaglia glacier (phase Daloo 10) (Fig. 15), cut by two San Giacomo moraines (Daloo 8 and 9). This implies that, during retreat, Engadina-Bregaglia glacier partly entered into San Giacomo Valley in some glacial phases, partially blocking or deviating San Giacomo glacier. While in the southern sector of San Giacomo glacier these retreat phases were taking place, in the northern area ice thickness was still almost at its maximum: a loss in thickness of hundreds of meters in the southern sector corresponded to a loss of few tens of meters, maybe even few meters in the northern zone (Bini A., 1996).

San Giacomo glacier retreat implied a loss of ice volume that resulted in a rapid abandonment of flat topography areas, as that of Pian dei Cavalli, accompanied by a similarly sudden advance of lateral glaciers. In phase San Giacomo 68 Pian dei Cavalli was already free from ice and the major glacier reached 2150 m a.s.l., which was about 150 m below trimline. By phase San Giacomo 65, San Giacomo glacier formed a narrow tongue in Febbraro Valley that reached the scarp which separated the lower from the upper valley. North of Febbraro Valley and Motta, on the opposite slope of the valley, the glacier was still in contact with lateral glaciers, while in the Andossi area during this phase (phase San giacomo 65) a particular evolution begins, testified by the great quantity of scattered erratics in this area (Fig. 2). At Andossi, while melting continues, the ice became too thin to allow flow of the glacier which, over this area, was blocked and became dead ice; at the same time in the two valleys contiguous to Andossi, Scalcoggia Valley in the west and Cardinello Valley in the east, the ice was thick enough to allow flow. The position of Andossi, and the setting of the dead ice area, progressively divided the San Giacomo glacier tongue. As melting proceeded, San Giacomo glacier passed from a single and very wide tongue that flowed almost from North to South covering all the Andossi area, to a smaller tongue forced to flow into Cardinello Valley, where it joined Ferrè glacier, and into Scalcoggia Valley where it joined Spadolazzo and Emet glaciers coming from NE (Fig. 16).

As the retreat proceeded, the glacier decreased in thickness and occupied only the bottom of San Giacomo and Cardinello valleys, leaving Andossi progressively devoid of dead ice. At phase San Giacomo 34, Andossi was completely free from active ice and the glacier reached Isola due to the flow of Ferré glacier, which, in this phase reached almost all the way down to the valley bottom. From phase San Giacomo 33 the glacier had completely retreated from Cardinello Valley and was progressively retreating into Loga Valley.

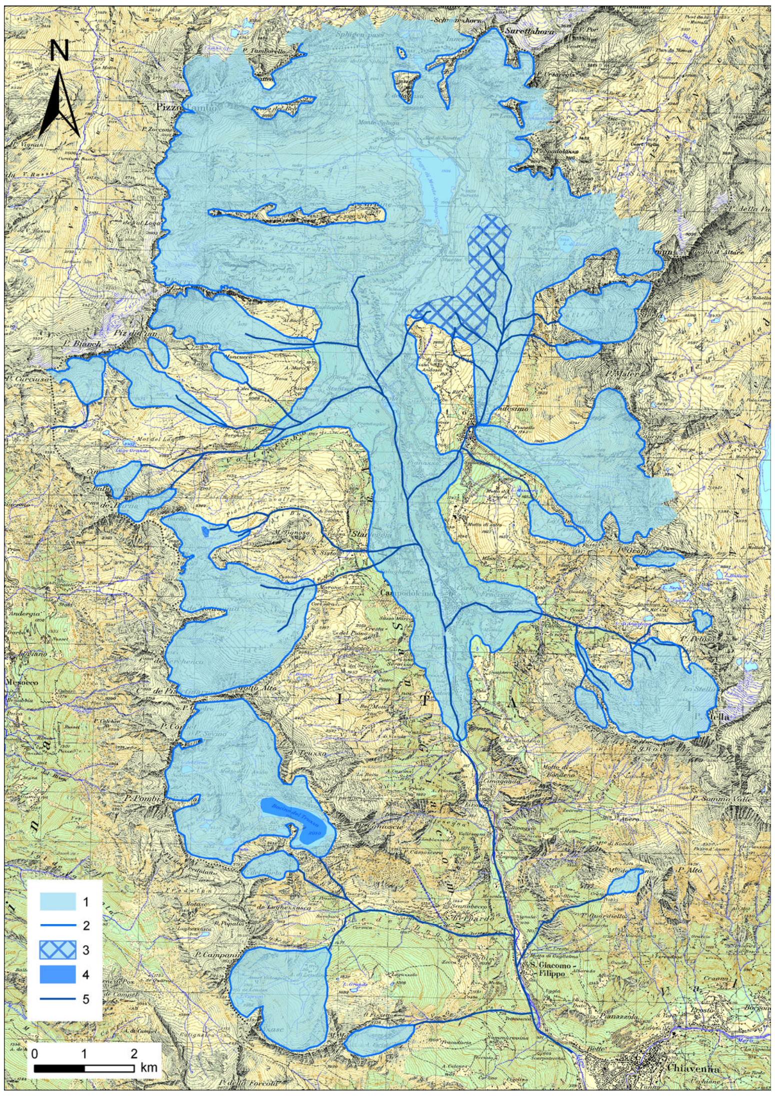

Fig. 16 - Extension of glaciated area in San Giacomo Valley during one of the last phases of the deglaciation. 1 – glacier; 2 – external border of the glaciers; 3 – dead ice; 4 – subglacial lake; 5 – subglacial and subaereous streams. The reconstruction is based on hypothetic correlations between the various glacial phases identified (Fig. 14), assuming as contemporaneous the glacial phases: San Giacomo 44, Ferrè S 9, Spadolazzo 6, Emet 14, Sterla 5, Fortezza E 5, Fortezza W 2, Vamlera 6, Latta 1, Piani N 1, Piani S 5, Bianco 2, Baldiscio 1, Bardan 2, Starleggia 5, Quadro 11, Groppera 2, Peloso 1, Angeloga A 1; Angeloga B 6, Angeloga C 6 Angeloga D 2, Truzzo 3, Cola 3, Crespallo 1.

6.2. Lateral glaciers

The most important lateral glacier is for certain Truzzo glacier which, during the maximum expansion, was united to Lendine glacier. The Drogo Valley morphology caused a rapid loss of mass of the two glaciers and separation from San Giacomo glacier when this reached ca. 1050 m above sea level and had a thickness of more than 400 m (phase Olmo 4, corresponding in the north with a San Giacomo phase comprised between 60 and 57), still blocked southward from the SE crest of Mount Mater. Lendine glacier retreated upwards in Lendine Valley leaving behind dead ice, while Truzzo glacier, occupying only Truzzo Valley, was hanging above the scarp below the dam (see Fig. 10).

Angeloga glacier divided from San Giacomo glacier during phase San Giacomo 49 or 50, when San Giacomo was approximately at 1500 m of altitude in Rabbiosa Valley and had a thickness exceeding 500 m. The topography of NW slope of Pizzo Stella, which contained Angeloga glacier, is such that the glacier during retreat divided into a series of separated minor glaciers.

Quadro and Starleggia glaciers descended Starleggia Valley with a low gradient until the sharp morphologic step that overlooks San Giacomo Valley, where these glaciers probably formed an ice fall towards San Giacomo glacier. It is not possible to infer in which phase the separation occurred, probably between San Giacomo 53 and 44 when San Giacomo glacier was over 500 m thick. As Sancia and Starleggia valleys have a relatively flat valley bottom, Quadro and Starleggia glaciers deposited a series of moraines (41 moraines, from 1750 m a.s.l. to 2600 m a.s.l.), even very long ones (in phases Quadro 3, Quadro 5, Quardo 12, Quadro 13, Quadro 14, Quadro 17), which recorded the retreat phases with a good detail (Fig. 17).

All the other lateral glaciers occupy more sloping valleys and with the retreat of San Giacomo glacier they advance towards the major valley bottom; the altitudes reached depend on the dimensions of the accumulation zone. Among these, the major are Emet, Fortezza, Ferré and Vamlera glaciers

7. CONCLUSIONS

Structural and geomorphological analysis of San Giacomo Valley (De Finis, 2012; Riganti, 2012; Taglieri, 2012; Tantardini, 2012) revealed that valleys in the Alps had a tectonic-structural origin, that is they formed during and because of tectonic movements. Moreover, the valley network had continuosly changed during the orogenesis, but the valleys already existed (Brugel et al., 2000; Spiegel et al., 2001). San Giacomo Valley has

Fig. 17 - Moraines of Starleggia Valley seen from the southern slope of the valley. The photo is taken from S towards N. Sancia glacier flowed from Sancia Valley, at W (beyond the left side of the photo); Starleggia glacier flowed from Starleggia valley, at NW (left-top corner of the photo). In this area the two glaciers joined in an only glacial tongue which flowed eastward. The western, more recent moraines of Starleggia-Sancia glacier forms a semicircular morainic amphitheatre in the area where the two glaciers joined, which partially erodes the eastern, more ancient, E-W oriented moraines.

been in its present-day position since the Miocene (Bernoulli et al., 1993; Bersezio et al., 1993; Carrapa & Di Giulio, 2001; Gelati et al., 1991; Giger & Hurford, 1989; Hansmann, 1996; Kuhlemann, 2007; Kuhlemann & Kempf, 2002; Sciunnach et al., 2004; Schlunegger et al., 1998; Schmid et al., 1996; Spiegel et al., 2001) and its morphology has varied only very slightly since the Messinian salinity crisis. In several alpine valleys, the erosive action of glaciers was minimal, and resulted from erosion and weathering occurred throughout all glaciations and not only throughout the last glacial maximum.

The study of glacial evidences in San Giacomo Valley allowed us to reconstruct the extension of glaciers at the LGM and during various phases of the deglaciation with a fairly good geometric precision.

Several alpine valleys similar to San Giacomo Valley, which initiate from the watershed ridge and are relatively short, did not host glacier tongues in ablation (except, in some cases, in their terminal part), but only the accumulation zone of the glaciers. Even if San Giacomo Valley has not a typical accumulation area morphology, it represented during the maximum expansion phase the zone of formation of ice. Over a length of ca. 25 km, the San Giacomo glacier ablation tongue occupied only the last 7 km of the valley. By contrast, during the deglaciation, the accumulation zone gradually shrank and moved upstream, while the ablation zone expanded. A similar evolution, but with inverse polarity, may have occurred during the glacial advance, although this remains speculative, giving that there is no evidence of this process.

Since the whole valley was the accumulation zone of ice, lateral valley glaciers during the maximum expansion were in direct continuity with the major glacier mass: there was no welding among the various glaciers, because actually they were the same glacier, the same glacial body. The only exception was Truzzo-Lendine glacier because it came from a lateral valley apart from San Giacomo Valley and, above all, because it joined San Giacomo glacier already in its ablation zone.

Throughout the deglaciation, lateral valley glaciers parted from the major glacier and gained progressively more importance. Most lateral glaciers reached their maximum extension at the complete retreat of the major glacier: in this moment lateral glaciers could flow downvalley a lot below trimline altitude.

Retreat phases recognizable in the valley and identified in the reconstructions identify only those glacial phases whose evidences remained. Building of lateral moraines or abandonment of erratics in particular positions (hills, ridges…) occured only in minor glacial advance events, which may not have had the same morphologic evidence (the same intensity, appearance, size) in the whole valley. It follows that our correlations (Fig. 14) are hypothetical, and based on present-day glacier geometry models (as in Bini et al., 2009). The absence of radiometric dating of moraines makes it impossible to establish assured correlations.

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REFERENCES

Ballantyne C. K. (1997) - Periglacial trimlines in the Scottish Highlands. Quaternary International, 38-39, 119-136.

Ballantyne C. K., McCarroll D., Nesje A., Dahl S. O., Stone J. O. (1998) - The last ice sheet in north-west Scotland: reconstructions and implications. Quaternary Science Reviews, 17, 1149-1184.

Ballantyne C. K., Stone J. O., McCarroll D. (2008) - Dimensions and chronology of the last ice sheet in Western Ireland. Quaternary Science Reviews, 27, 185-200.

Benn D.I., Evans D.J.A. (1998) - Glaciers and glaciation. Edward Arnold, London, UK, pp. 734.

Bernoulli D., Giger M., Muller D.W., Ziegler U.R.F. (1993) - Sr-isotope stratigraphy of the Gonfolite Group ("South-Alpine Molasse", northern Italy) and radiometric constraints for its age of deposition. Eclogae Geologicae Helvetiae, 86, 751-767.

Bersezio R., Fornaciari M., Gelati R., Napolitano A., Valdisturlo A. (1993) - The significance of the Upper Cretaceous to Miocene clastic wedge in the deformation history of the Lombardian Southern Alps. Géologie Alpine, 69, 3-20.

Biella G., de Franco R., Caielli G., Vignola P., Lozej A., Bini A., Guglielmin M., Carbonara S., Terenzoni M. (2001) - Imaging the deposits that fill Valtellina (NW Italy) by seismic reflection investigation. 5th Workshop Alpine Geological Studies. Geol. Paläont. Mitt. Innsbruck, 25, 33-34.

Bini A. (1994) - Rapports entre la karstification periméditerranéenne et la crise de salinité du Messinien: l'exemple du karst Lombard. Karstologia, 23, 33-53.

Bini A. (1996) - La massima estensione dei ghiacciai (MEG) nel territorio compreso tra il Lago di Como, il Lago Maggiore e le rispettive zone di anfiteatro.

Bini A. (1997) - Problems and methodologies in the study of the quaternary deposits of the southern side of the Alps. Southern Alps Quaternary Geology, IGCP 378 Meeting, Lugano, CH, october 1995. Geologia Insubrica, 2(2), 11-20.

Bini A. (1999) - Dispense di Geologia del Quaternario. Geologia del glaciale in montagna. AIQUA.

Bini A., Felber M., Pomicino N., Zuccoli L. (1997) - Stratigraphy, chronology and palaeogeography of Quaternary deposits of the area between the Ticino and Olona rivers (Italy-Switzerland). Southern Alps Quaternary Geology, IGCP 378 Meeting, Lugano, CH, october 1995. Geologia Insubrica, 2(2), 21-46.

Bini A., Buoncristiani J.-F., Couterrand S., Ellwanger D., Felber M., Florineth D., Graf H. R., Keller O., Kelly M., Schlüchter C., Schoeneich P. (2009) - Die Schweiz während des letzteiszeitlichen Maximums (LGM). Bundesamt für Landestopografie swisstopo.

Bini A., Cita M.B. e Gaetani M. (1978) - Southern alpine lakes: hypothesis of an erosional origin related to the Messinian entrenchment. Marine Geology, 27, 271-288

Bini A., Giannini F., Gotti D. (2012) - Evidenze glaciali precedenti lo LGM in Val Tartano e Val d'Arigna. In press.

Bini A., Pellegrini A. (1998) - Geologia del Quaternario. In Bini A., Pellegrini A. (eds): Il Carsismo del Moncodeno (Ricerche sugli aspetti del fenomeno carsico profondo nel Gruppo delle Grigne: VII Il carsismo del Moncodeno). Geologia Insubrica, 3(2), 37-56.

Bowen D. Q. (1978) - Quaternary geology: a stratigraphic framework for multidisciplinary work. Pergamon, pp. 221.

Brambilla G., Lualdi A. (1986) - Il Pliocene della Provincia di Bergamo (Italia settentrionale). Analisi faunistica ed inquadramento cronologico e paleomabientale. Boll. Soc. Paleont. Ital., 25(3), 237-266.

Brügel A., Dunkl I., Frisch W., Kuhlemann J., Balogh K. (2000) - The record of the Periadriatic volcanism in the Eastern Alpine Molasse zone and its palaeogeographic implications. Terra Nova, 12, 42-47.

Carrapa B., Di Giulio A. (2001) - The sedimentary record of the exhumation of a granitic intrusion into a collisional setting: the lower Gonfolite Group, Southern Alps, Italy. Sedimentary Geology, 139, 217-228.

Cita M.B., Bini A., Corselli C. (1990) - Superfici di erosione messiniane: una ipotesi sull'origine dei laghi sud - alpini. In: Barbanti L., Giussani G., De Bernardi R. (eds): Il Lago Maggiore dalla ricerca alla gestione. Simp. 50° Anniv. Fondaz. Ist. It. Idrobiol., Pallanza, 1988, 33-54.

Cita M.B., Corselli C. (1990) - Messinian paleogeography and erosional surfaces in Italy: an overview. Palaeogeography, Palaeoclimatology, Palaeoecology, 77, 67-82.

Cita M.B., Corselli C. (1993) - Messiniano: vent'anni dopo. Mem. Soc. Geol. It., 49, 145-164.

Cloos H. (1925) - Einführung in die tektonische Behandlung magmatischer Erscheinungen (Granittektonik), I. Spezieller Teil. Das Riesengebirge in Schlesien. Bau, Bildung, und Oberflachengestältung. Borntraeger, Berlin, pp. 194.

Corselli C., Cremaschi M., Violanti D. (1985) - Il canyon messiniano di Malnate (Varese): pedogenesi tardomiocenica ed ingressione marina pliocenica al margine meridionale delle Alpi. Riv. It. Paleont. Strat., 91(2), 259-286.

Comolli R., Bernardelli E., Ferrè C. (2011) - Pedologia: tipi di suolo e loro caratteristiche. In: Aldighieri B., Mazzoleni G. (eds.) (2011). La Valchiavenna: un bacino pilota per il controllo dell'ambiente alpino. Quaderni di Geodinamica alpina e Quaternaria, I.D.P.A., C.N.R., Milano.

Darnault R., Rolland Y., Braucher R., Bourlès D., Revel M., Sanchez G., Bouissou S. (2012) - Timing of the last deglaciation revealed by receding glaciers at the Alpine-scale: Impact on mountain geomorphology. Quaternary Science Reviews, 31, 127-142.

De Finis E. (2012) - Cartografia geomorfologica della Val San Giacomo (in preparation for printing).

Felber M., Frei W., Heitzmann P. (1991): Seismic evidence of pre - pliocene valley formation and filling in the region of Novazzano (Southern Ticino, Switzerland). Eclogae Geol. Helv., 84(3), 753-761.

Felber M., Bini A., Heitzmann P., Frei W. (1994) - Evidenze sismiche di valli sepolte nel Mendrisiotto e nel Piano di Magadino (Ticino, CH). Proc. Symp. "Crop - Alpi Centrali, Sondrio 1993, in: Quaderni di Geodinamica Alpina e Quaternaria, 2, 103-133.

Felber M., Bini A. (1997) - Seismic survey in alpine and prealpine valleys of Ticino (Switzerland): evidences of a Late-Tertiary fluvial origin. Southern Alps Quaternary Geology, IGCP 378 Meeting, Lugano, CH, october 1995. Geologia Insubrica, 2(2): 46-47.

Finchk P.G. (1978) - Are Southern Alpine lakes former Messinian canyons? Geophysical evidence for pre-glacial erosion in the Southern Alpine lakes. Marine Geol., 27, 289-302.

Finckh P., Kelts K., Lambert A. (1984) - Seismic stratigraphy and bedrock forms in perialpine lakes. Bull. Geol. Soc. Am., 95, 1118-1128.

Florineth D. (1998) - Surface geometry of the Last Glacial Maximum (LGM) in the southeastern Swiss Alps (Graubünden) and its paleoclimatological significance. Eiszeitalter und Gegenwart, 48, 23-37.

Florineth D., Schlüchter C. (1998) - Reconstructing Last Glacial Maximum (LGM) ice surface geometry and flowlines in the Central Swiss Alps. Eclogae geologicae Helvetiae, 91, 391-407.

Gelati R., Napolitano A., Valdisturlo A. (1991) - Results of studies on the Meso-Cenozoic succession in the Monte Olimpino 2 tunnel. The tectono-sedimentary significance of the "Gonfolite Lombarda". Rivista Italiana di Paleontologia e Stratigrafia, 97, 565-598.

Giger M., Hurford A.J. (1989) - Tertiary intrusives of the Central Alps: their Tertiary uplift, erosion, redeposition and burial in the south-alpine foreland. Eclogae Geologicae Helvetiae, 82, 857-866.

Hambrey M.J. (1994) - Glacial environments. University College London Press, London, 296 pp.

Hansmann W. (1996) - Age determination on the Tertiary Masino-Bregaglia (Bergell) intrusives (Italy,Switzerland): a review. Schweizerische mineralogische und petrographische Mitteilungen, 26(3), 421-451.

Ivy-Ochs S., Kerschner H., Reuther A., Maisch M., Sailer R., Schaefer J., Kubik P.W., Synal H.A., Schlüchter C., (2006) - The timing of glacier advances in the northern European Alps based on surface exposure dating with cosmogenic ^{10}Be, ^{26}Al, ^{36}Cl, and ^{21}Ne (Conference Paper). Special Paper of the Geological Society of America, 415, 43-60.

Ivy-Ochs S., Kerschner H., Reuther A., Preusser F. Heine K. Maisch M., Kubik P.W., Schlüchter C. (2008) - Chronology of the last glacial cycle in the European Alps. Journal of Quaternary Science, 23, 559-573.

Ivy-Ochs S., Kerschner H., Maisch M., Christl M., Kubik P.W., Schlüchter C. (2009). Latest Pleistocene and Holocene glacier variations in the European Alps. Quaternary Science Reviews, 28, 2137-2149.

Kelly M.A., Buoncristiani J.F., Schlüchter C. (2004). A reconstruction of the last glacial maximum (LGM) ice-surface geometry in the western Swiss Alps and contiguous Alpine regions in Italy and France. Eclogae Geologicae Helvetiae, 97, 57-75.

Kuhlemann J. (2007) - Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Global and Planetary Change, 58, 224-236.

Kuhlemann J., Kempf O. (2002) - Post-Eocene evolution of the North Alpine Foreland Basin and its response to Alpine tectonics. Sedimentary geology, 152, 45-78.

Lualdi A. (1981) - Il Pliocene di Clanezzo in Vall'Imagna (Bergamo): indagine faunistica. Atti Ist. Geol. Univ. Pavia, 29,120-127.

Maggi V. (1992) - Geologia del Quaternario del monte Berlinghera e del Pizzo Sasso Canale (Provincia di Como). Il Quaternario, 5(2), 235-250.

Migòn P. (2006) - Granite landscapes of the world. Oxford University Press, pp. 384.

Montrasio A., Berra F., Cariboni M., Ceriani M., Deichmann N., Ferliga C., Gregnanin A.,Guerra S., Guglielmin M., Jadoul F., Longhin M., Mair V., Mazzoccola D., Sciesa E., Zappone A. (2012) - Note Illustrative alla Carta Geologica d'Italia alla scala 1: 50.000. Foglio 024 Bormio.

Penck A., Brückner E. (1909) - Die Alpen im Eiszeitalter. Dritter Band. Die Eiszeiten in den Sudalpen und im Bereich der Ostabdachung der Alpen. Tauchnitz, Leipzig.

Perello P., Gianotti F., Monopoli B., Carraro F., Venturini G., Fontan D., Schiavo A., Bonetto F. (2011) - Note illustrative della Carta Geologica d'Italia alla scala 1:50.000. Foglio 089 Courmayeur.

Quattrone P., Rogledi S., Longoni R. (1990) - Gas fields in the Tertiary sequences of the Milano Bergamo Region. Bull. Ver Schweiz. Petroleum-Geol. u. - Ing., 57, 53-64.

Richmond G.M. (1986) - Stratigraphy and chronology of glaciations in Yellowstone National Park. In: Šibrava V., Bowen D.Q., Richmond G.M. (eds.): Quaternary glaciations in the Northern Hemisphere. Report IGCP n°24, Quaternary Science Reviews, 5(1-4), 83-98.

Reitner, J.M. (2007) - Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications. Quaternary International, 164-165, 64-84.

Richmond G.M., Fullerton D.S. (1986) - Summation of Quaternary glaciations in the United States of America. In: Šibrava V., Bowen D.Q., Richmond G.M. (eds.): Quaternary glaciations in the Northern Hemisphere. Report IGCP n°24, Quaternary Science Reviews 5(1-4), 183-196.

Riganti N. (2012) - Studio della Geologia del Quaternario e della Geomorfologia del versante destro della media Val San Giacomo, compresa tra il Piano dei Cavalli e l'Alpe Boggi, e ricostruzione delle fasi relative all'ultimo massimo glaciale. Università degli Studi di Milano. Unpublished graduation thesis.

Rizzini A., Dondi L. (1978) - Erosional surface of Messinian age in the subsurface of the Lombardian plain (Italy). Marine Geology, 27, 303 - 325.

Rutishauser V. (1986) - Das Südtessin im Neogen: zwischen Schuttstrom und Schelfmeer. Eine Fazies- und Ablagerungsraumanalyse. Diss. ETH Zürich, pp. 151.

Sciesa E. (1991) - Geologia delle Alpi centrali lungo la traversa Colico-Passo dello Spluga (Province di Sondrio e Como). Il Naturalista Valtellinese. Atti Mus. Civ. Stor. Nat. Morbegno (2), 3-34.

Sciunnach D., Tremolada F. (2004) - The Lombardian Gonfolite Group in central Brianza (Como and Milano Provinces, Italy): Calcareous nannofossil biostratigraphy and sedimentary record of neo-alpine tectonics. Eclogae Geologicae Helvetiae, 97(1), 119-131.

Šibrava V., Bowen D. Q., Richmond G. M. (1986) - Quaternary glaciations in the northern hemisphere. (Report of the International Geological Correlation Programme. Project 24). Quaternary science reviews, 5, pp. IX-511.

Schlunegger F., Slingerland R., Matter A. (1998) - Crustal thickening and crustal extension as controls on the evolution of the drainage network of the Central Swiss Alps between 30 Ma and the present: constraints from the stratigraphy of the North Alpine Foreland Basin and the structural evolution of the Alps. Basin Research, 10, 197-212.

Schmid S.M., Pfiffner O.A., Froitzheim N., Schönborn G., Kissling E. (1996) - Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics, 15(5), 1036-1064.

Spiegel C., Kuhlemann J., Dunkl I., Frisch W. (2001) - Paleogeography and catchment evolution in a mobile orogenic belt: the Central Alps in Oligo-Miocene times. Tectonophysics, 341, 33-47.

Starnberger R. , Rodnight H., Spötl C. (2011) - Chronology of the Last Glacial Maximum in the Salzach palaeoglacier area (Eastern Alps). Journal of Quaternary Science, 26, 502-510.

Stevenazzi S. (2010) - Dinamica di versante e ricostruzione del ghiacciaio durante l'ultimo massimo glaciale in Val Bregaglia, versante destro, comune di Villa di Chiavenna (SO). Unpublished graduation thesis.

Taglieri P. (2012) - Studio della Geologia del Quaternario e della Geomorfologia del versante destro dell'alta Val San Giacomo, compresa tra la Valle Scisarolo e la Val Febbraro, e ricostruzione delle fasi relative all'ultimo massimo glaciale. Università degli Studi di Milano. Unpublished graduation thesis.

Tantardini D. (2012) - Studio della geologia del Quaternario e della geomorfologia della sponda destra della bassa Val San Giacomo tra la Valle di Servizio e la Valle del Drogo, e ricostruzione delle fasi relative all'ultimo massimo glaciale. Università degli Studi di Milano. Unpublished graduation thesis.

Van der Beek P., Bourbon P. (2008) - A quantification of the glacial imprint on relief development in the French western Alps. Geomorphology, 97 (1-2), 52-72.

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