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STRATIGRAPHY OF THE IVREA MORAINIC AMPHITHEATRE (NW ITALY): AN UPDATED SYNTHESIS

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ABSTRACT: The Ivrea Morainic Amphitheatre (IMA) is the main evidence of Quaternary glaciations in the Dora Baltea basin (NW Italy). This end moraine system forms a 500 km2 wide complex of lateral and terminal moraines and kame terraces, dated from the end of the Early Pleistocene (on palaeomagnetic basis) to the end of the Late Pleistocene (^{14}C radiometric and ^{10}Be exposure ages). A synthesis of the state of the art on the IMA stratigraphy is presented, based on the previous literature and reinterpreted in the light of new surveys and dating. Some embedded palaeosols and palustrine deposits within the glacigenic sequences, interpretable the first as interglacial layers and the latter as interglacial or interstadial layers, crop out along stream incisions cutting the IMA outer and inner edges or were sampled through boreholes (Alice Superiore and Torre Canavese cores). The top of the deposits shows different degrees of weathering and they can be distinguished into three pedogroups based on the hue index color of the soil horizons. Buried stratigraphical markers and pedogroups together allowed the subdivision of the glacigenic succession into nine stratigraphic units (Mongrando, Bornasco, Montino and Zubiena synthems, grouped in the 2.5YR pedogroup; Parogno and Torrazzo synthems, grouped in the 5YR pedogroup; Magnano, Serra and Ivrea synthems, grouped in the 7.5YR pedogroup). Each synthem has been attributed to different glacial expansion. So a potentially complete glacigenic succession outcrops, which can be possibly correlated to the whole sequence of the main Quaternary glaciations of the marine oxygen isotope stratigraphy from MIS 22-20 to MIS 2. The widest unit (Serra synthem), related to the penultimate glaciation (MIS 6), comprises the Serra d'Ivrea lateral moraines and is subdivided into two sub-units (External Serra and Internal Serra subsynthems) on morphological grounds. The innermost unit (Ivrea synthem) related to MIS 2 is subdivided into 13 sub-units on morphological basis, corresponding to the height of the Last Glacial Maximum (Piverone subsynthem), to six LGM retreat stadials in amphitheatre (Palazzo, Quintas, Pavone, Bienca, Prà San Pietro and Germano subsynthem) and six LGM-Lateglacial stadials in the Dora Baltea Valley.

KEYWORDS: glacial stratigraphy, glaciations, end moraine system, Pleistocene, Western Alps, LGM

1. INTRODUCTION

Morainic amphitheatres are the most direct evidence of the extent of mountain glaciers during Pleistocene glaciations. These morainic reliefs are preserved in all of the middle latitude mountain chains. They form broad amphitheatres in the Andes, in New Zealand and in the European Alps, and subordinately in the Rocky Mountains and in the Chinese Himalaya, i.e. where glaciers could spread out over the piedmont plains (Ehlers & Gibbard, 2004a, b, c).

The Ivrea morainic amphitheatre (IMA) is located at the outlet of the Aosta Valley (Fig. 1). Among the end moraine systems of the southern side of the Alps, the IMA is well known for its remarkable geomorphology. It is one of the largest (505 km^2) morainic amphitheatres, although smaller than the Garda and Verbano amphitheatres. It contains two distinctive morphological elements: 1) the Serra d'Ivrea lateral moraine, which is the highest expression of glacial sedimentation; 2) the Ivrea Hills (*Colli d'Ivrea*), where evidence of subglacial erosional processes is abundant. Because of its morphological characteristics the IMA was defined as the most considerable amphitheatre of the Alpine glaciation (Penck et al., 1894).

Also the stratigraphical features are particularly remarkable. The amphitheatre was apparently built during most of the interglacial-glacial cycles of the second half of the Quaternary, as nine stratigraphical units have been distinguished (Gianotti et al., 2008) related to as many main glacial expansions ranging in age from the end of the Early Pleistocene to the Late Pleistocene.

The aim of the present work is to synthesize the state of the art about the IMA stratigraphy, taking into account the long historical background proved by more than 100 geological publications starting from 1850 AD.

2. GEOLOGICAL SETTING

The IMA is located in the western Po Plain at the outlet of the Aosta Valley, up to about 120 km from the present fronts of the Monte Bianco glaciers (Fig. 1). The morainic hills are spread in the Po Plain for more than half of its width (24 km on a total of 42 km). The remnant space is filled mostly by the IMA glaciofluvial sandur, forming a 500 km^2 terraced system. The Po River, the trunk river of the plain, flows within a 1.5-3 km large alluvial corridor between the rims of the frontal sandur and the northern slopes of the Collina di Torino-Monferrato.

The strong morphological evidence of the IMA (Fig. 2) is a consequence of the very elevated topography (mean elevation of 2100 m a.s.l. with 90% of the area lying above 1500 m a.s.l.) and the proximity of its mountain catchment area. The Aosta Valley is a 3350 km^2 wide branched mountain basin, consisting of a 100 km long main valley (Dora Baltea Valley) and of about thirty major tributary valleys. It is bounded by some of the highest peaks of the European Alps, rising a short distance from the Po Plain. In detail Monte Bianco (4812 m) and Gran Paradiso (4061 m) are 95 km away from the valley outlet at Borgofranco d'Ivrea (250 m a.s.l.), where the IMA begins, while Cervino (4478 m) and Monte Rosa (4634 m) are only 60 and 45 km away, respectively. The altitude promotes the existence of several glaciers (209) with an overall present-day extent of approximately 135 km^2 (Aosta Valley Catalogue of Glaciers, 2005), corresponding to 4.0 % of the basin.

The Dora Baltea Valley is deeply incised across the inner and axial sectors of the Western Alps. The latter are part of a typical collisional belt developed from the Cretaceous by subduction of a Mesozoic ocean and collision between the Adriatic (Austroalpine-Southalpine) and European (Penninic-Helvetic) continental margins (Dal Piaz et al., 2003). With the partial exception of the nearby Ossola-Ticino valley system, the Dora Baltea is the only basin of the whole Alps to cut all the main structural domains that constitute the Alpine range, i.e. from the Southern Alps across the entire Alpine Axial Belt (Austroalpine and Penninic units), up to the inner border of the External Zone (Helvetic units).

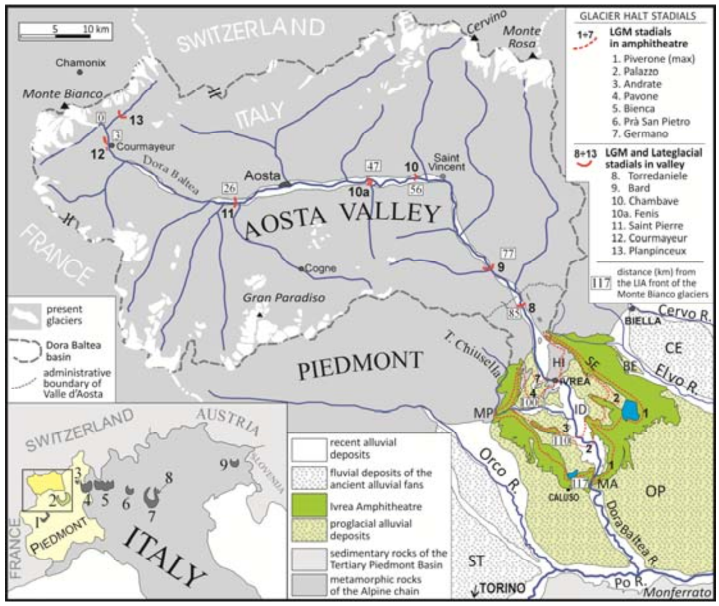


Fig. 1 - Geomorphological sketch map of the Dora Baltea basin, with the 3400 km^2 wide mountain basin nearly corresponding to Valle d'Aosta region and the IMA at the outlet of the valley (from Gianotti et al, 2008, mod.). The present glaciers of the basin are shown. The bedrock crops out in the IMA inner sector in the granulite Ivrea Hills (HI) and in the outer western sector in the Monti Pelati peridotite reliefs (MP). The Serra d'Ivrea moraine (SE), the inner depression (ID) and the outer outwash plain (OP) are pointed out. The Dora Baltea River flows out of the IMA through the Mazzé gorge (MA). At the northeastern edge the Bessa roman gold mines extend (BE). The Stura di Lanzo (ST) and Cervo (CE) fan complexes spread laterally to the IMA. LGM to Lateglacial stadials in Colli d'Ivrea area and in the valley are shown. Main morainic amphitheatres of Italian Alps (box at the bottom left): 1) Rivoli-Avigliana (Susa Valley); 2) Ivrea (Dora Baltea Valley); 3) Orta (Strona Valley); 4) Verbano (Ossola+Ticino valleys); 5) Lario (Valtellina and Como Lake); 6) Iseo (Camonica Valley); 7) Garda (Adige-Sarca valleys); 8) Rivoli Veronese (''Lagarina'' Valley); 9) Tagliamento (Tagliamento Valley).

The complex lithologic composition of the basin (Elter, 1987; De Giusti et al., 2004) is mirrored in the large petrographic variety of the glacigenic deposits found in the IMA, made of silicate and subordinate carbonate metamorphic rocks.

Concerning the IMA underlying rock, in its proximal sector the IMA lies on metamorphic bedrock with formations spanning from the Variscan (Paleozoic) to the Alpine (Cretaceous - Oligocene) cycle (Figs. 3A-B). In contrast, the middle and distal sectors of the IMA rest on marine, transitional and alluvial sequences of Zanclean-Early Pleistocene age (Figs. 3C-F). This setting is typical of the big Italian piedmont end moraine systems (i.e. Rivoli-Avigliana, Verbano, Lario, Garda and Tagliamento).

The bedrock is comprised of continental crust of the Adriatic Plate, made of Austroalpine eclogitic micaschists to the NW (Sesia-Lanzo Zone; Compagnoni et al., 1977; Venturini, 1995) and of Southalpine rocks to the SE (Ivrea-Verbano Zone and Canavese Zone). The

Fig. 2 - Panorama of the IMA (view from the Bric Paglie slope at 1200 m a.s.l.)

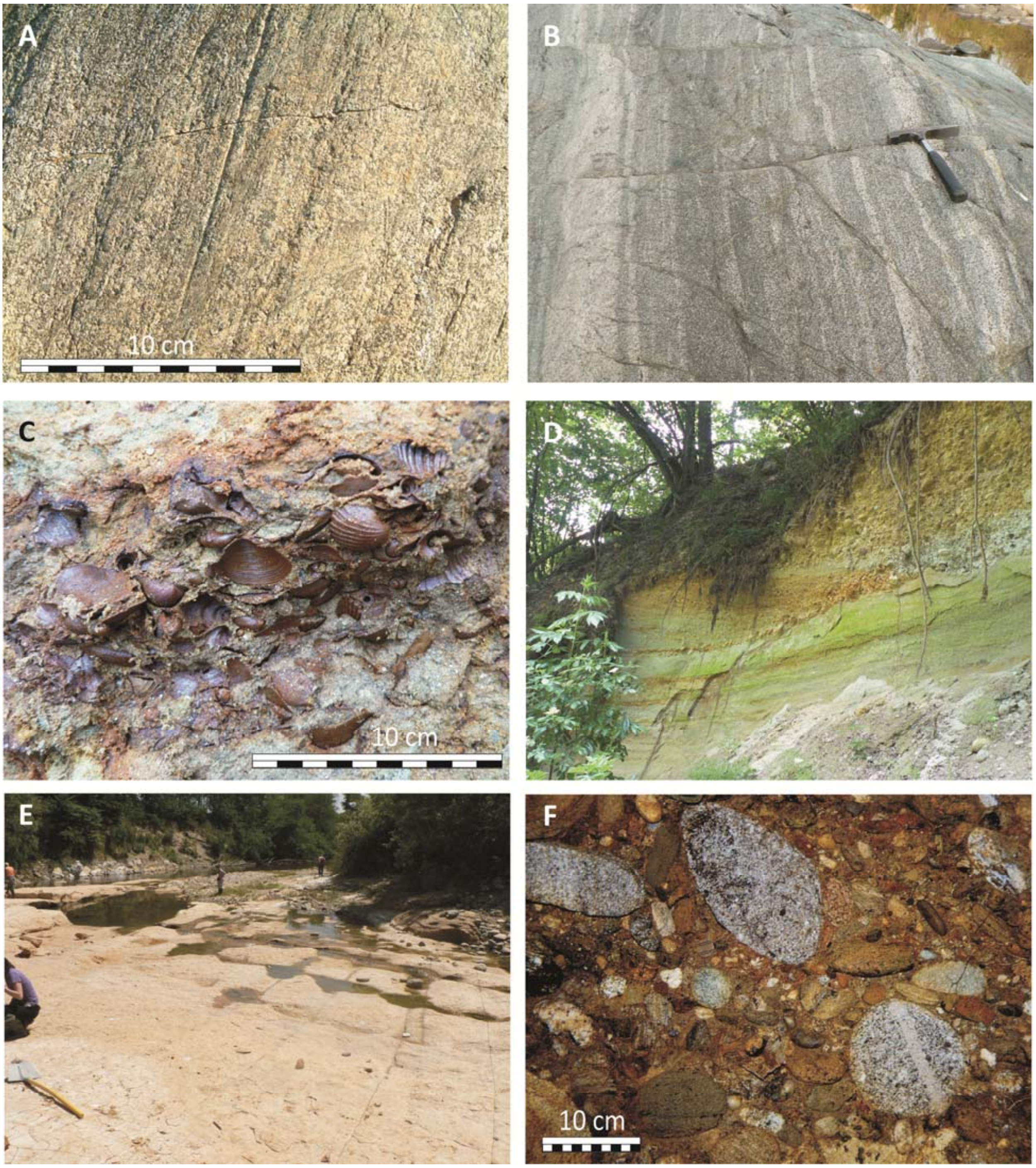


Fig. 3 - The various lithotypes that constitute the IMA substrate. (A) Basic granulite of the Ivrea Verbano Zone forming the bedrock cropping out in the Chiusella R. riverbed (Ponte dei Preti, Strambinello). (B) Polished and striated basic granulite in the Ivrea Hills (Montalto Dora). (C) Zanclean fossiliferous marine sediments into the Strambinello LS (Peronetto, South of Parella). (D) Estuarine transitional sand and gravel cropping out into the Borra Grande incision (Peronetto, South of Parella). (E) Fractured villafranchian sandy silt, recently exposed into the Elvo riverbed. (F) Deeply weathered fluvial gravel referred to the pre-glacial Dora Baltea fan (Cerrione synthem), cropping out in the Valle Sorda riverbed (west of Cerrione).

two systems meet along the External Canavese Line (ECL in Figs. 4 and 5), that is part of the Periadriatic Line delimiting the internal edge of the Alpine Axial Belt. This transversal fault marks the contact of the Alpine high-pressure metamorphic rocks (Austroalpine System) with the pre-Alpine Variscan basement (Southalpine System) and morphologically separates the higher Alpine range from the low Ivrea Hills. A second sub-parallel fault (the Internal Canavese Line; ICL in Figs. 4 and 5) intersects the Southalpine basement bringing the Ivrea-Verbano Zone deep continental crust into contact with the Canavese Zone shallow continental crust. The Canavese Zone (Biino & Compagnoni, 1989) comprises a Variscan, low-grade metamorphic basement (schist) with Permian granitic and dioritic intrusions and a Permo-Mesozoic sedimentary cover made of breccias, volcanics, quartzites and dolomites. The Ivrea-Verbano Zone (Zingg et al., 1990), forming the most of the Ivrea Hills, is here constituted by the Permian Ivrea gabbro batholith, re-equilibrated in high-grade mafic granulite facies (Fig. 3A).

Faults and related fractures have promoted and guided subglacial erosion during glaciations. The tectonic constraints influenced the directions of glacial flow and the continuity of marginal forms, particularly at the outlet of the Dora Baltea valley, where the glacier split into glacial lobes that crossed the low watershed separating the Dora Baltea basin and the Chiusella Valley (Fig. 4; see 3).

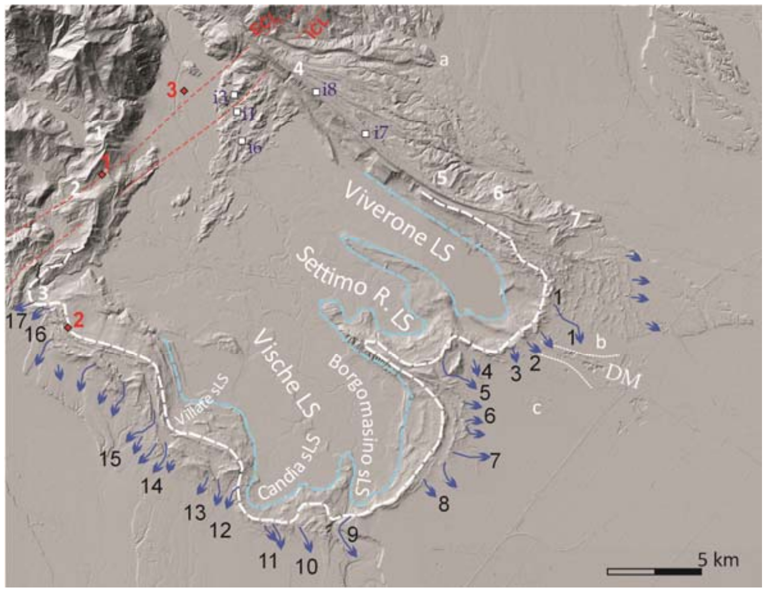


Fig. 4 - The main glacial lobe (LS) and sub-lobe (sSL) systems are marked on the DTM of the IMA by dashed white line (during Internal Serra stadial) and blue dashed line (during Piverone stadial). Other minor LS are reported (white numbers): Riccardi (1), Alice Superiore (2), Strambinello (3), Pré Lake (4), Magnano (5), Santo Sudario (6), Salussola (7). The locations of the drill cores used for stratigraphic reconstruction are mapped with red symbols (1: Alice Superiore; 2: Torre Canavese; 3: Montalto Dora). The erratic boulders dated with cosmogenic nuclide dating method are pointed out by white squares (i7 and i8 on the External Serra crest; i1, i3 and i6 in the Ivrea Hills). Black numbers indicate the spillway/glaciofluvial fan systems forming the proximal sandur. From east to west they are the spillways of Cavaglià (1), Dora Morta (2), Passo d'Avenco (3), Sapel da Bras (4), Bocca d'Arbaro (5), Suc (6), San Maurizio (7), Moncrivello (8), Mazzè (9), Valle della Motta (10), the three opening of Caluso (11), Candia (12), Barone Canavese (13), Montalenghe (14), outer Taglio Grosso (15), Ronchi (16) and Pramonico (17). Letters indicates elements explained in the text.

The Pliocene sedimentary succession lies on the metamorphic bedrock, ranging from marine to transitional sediments. Remarkable outcrops of Pliocene deposits are well known in the western internal sector of the IMA, from the classical fossil-bearing sites (Ponte dei Preti and Borra Grande) into the Strambinello lobe apparatus up to the Rio Borriana incision. The succession crops out for about 70 m of thickness (275-345 m a.s.l.) between Pranzalito and Pian Torinetto on the right side of the T. Chiusella incision (Martinetto, 1998; Basilici et al., 1998). A basal unit of fine sand with scarce gravel lenses, intensely bioturbated and with abundant fossil mollusc shells (Fig. 3C) is referred to the infralittoral zone and dated to the Zanclean-Piacenzian boundary. They pass upwards to transitional sediments (Fig. 3D) correlatable to the “Villafranchian lower complex” of the Villafranca d’Asti type-area of Piacenzian age (Carraro, 1996; Caramiello et al., 1996; Forno et al., in press).

Whereas, a series of continental units, made up of deeply weathered fluvial sandy gravel, can be correlated to the “Villafranchian upper complex” (Lower Pleistocene). They form wide terraces (named *altopiani villafranchiani* in Bortolami et al., 1966) in the northeastern sector of the IMA. Carraro et al. (1991) distinguished four units of torrential coarse gravels linked to the pa-

Fig. 5 - Longitudinal profile of the Ivrea Amphitheatre with the Serra of Ivrea morainic group. The Serra d’Ivrea is morphologically divided into External Serra (brown) and Internal Serra (blue). A deep glacial excavation hollow in correspondence of the Canavese Zone bedrock (black asterisk), whose bottom is below sea level, was discovered by means of a 270 m deep coring at Montalto Dora. The Ivrea Hills represent the threshold by which the Aosta Valley is perched above the Po Valley.

laeo-Elvo alluvial fan, forming fluvial terraces suspended at decreasing elevation above the current riverbeds: only the Graglia unit and the underlying Garabello unit pre-date the IMA formation. The following Muzzano unit is coeval with the first glacigenic unit of the IMA (Mongrando synthem) and the Camburzano unit is referred to the Middle Pleistocene. Southward in the Bessa terrace a fluvial unit made of medium-fine gravel and sand crops out below the remnant glacigenic cover (Fig. 3F). It is part of the pre-glacial Dora Baltea alluvial fan (Cerrione unit), coeval with the pre-glacial Elvo fan (Graglia unit). These two heteropic units constitute the IMA substrate in the outermost edge of its eastern sector (Gianotti, 1993). Other similar gravel and sand successions, of doubtful stratigraphic attribution, crop out in the Dora Baltea incision at Mazzé and at the base of the high terrace scarp in the southeastern sector (Brianco terrace between Salussola and Carisio) and in the southwestern sector (between Foglizzo and Aglié).

3. GEOMORPHOLOGICAL SETTING OF THE IMA

The IMA forms a huge complex of lateral and terminal moraines and kame terraces (300 km^2) around a large internal depression (200 km^2). This 500 km^2 wide complex constitutes the amphitheatre *sensu strictu* (Fig. 2). All around the IMA there is an equally wide apron of glaciofluvial deposits forming a suspended plain, corresponding to the classical sandur of the end moraine systems. IMA together with its proglacial sandur form a Pleistocene glacigenic depositional system with an extent of over 1000 km^2 genetically linked to the Dora Baltea /Aosta Valley basin. Compared to the other Alpine end moraine systems, the IMA is characterized by: (i) the Serra d'Ivrea, an exceptionally regular and very long (16 km) lateral moraine, regarded as the biggest of the Alps (Penck & Brückner, 1909); (ii) a very large fluvial plain occupying the internal depression; (iii) the Ivrea Hills, a 21 km^2 wide sub-glacially moulded bedrock relief, rising on the internal plain. The spectacular landscape of the IMA, that impressed many scientists (i.e. Gastaldi defined it the most important geological evidence in the upper Po Valley) is based on the contrast between the flat internal plain and the surrounding high morainic reliefs, with a sharp difference of elevation reaching 700 m. The IMA is constituted of four main morphological sectors: the morainic relief, the internal plain, the subglacially moulded Ivrea Hills and the external plain.

The <u>morainic relief</u> shows numerous alignments (up to about 40 in the eastern sector) of ice marginal position landforms, corresponding to lateral and frontal moraines and kame terraces. In addition to the ancient Sacco map (1938), only Zienert (1970) carried out geomorphological analysis on the IMA and identified 28 morainic circles. These landforms are arranged in 3 main glacial lobe systems (LS): Viverone, Settimo Rottaro and Vische. In the western sector of IMA the smaller LS of Alice Superiore and Strambinello are present (Fig. 4). Every one of them is constituted by a system of lateral and frontal moraines encircling an internal depression. The Viverone LS comprises the Serra d'Ivrea, which forms its left lateral moraine, and surrounds the Viverone Lake (230 m a.s.l., max deep 58 m). The Vische LS is the widest, is crossed along the entire length by the Dora Baltea River and is branched into three sub-lobes: the Borgomasino sub-LS, with the Mazzé gorge by which the Dora Baltea R. flows out the amphitheatre; the Candia sub-LS encircling the Candia Lake (226 m a.s.l., 7.5 m deep); and the less evident Villate sub-LS. The smallest Settimo Rottaro LS is comprised between the Viverone and Vische LS and has an inner plain derived from the filling of a palaeo-lake at the same elevation (230 m a.s.l.) of Viverone Lake. In the sector of the IMA close to the valley outlet, the presence of the Canavese Zone influenced the path of smaller ice lobes in which the glacier was split. The Alice Superiore LS is clearly aligned with the External Canavese Line, which channelled and confined glacial erosion into the belt of fractured bedrock of the Canavese Zone. The Strambinello lobe repeatedly dammed the outlet of the Chiusella Valley, causing the diffluence of the Chiusella stream toward the SW to confluence with the Orco River.

The <u>Ivrea Hills</u> correspond to the Southalpine basement outcropping over a wide area (21 km^2) in the internal depression of the amphitheatre. They are a group of low hills with gentle smooth morphology, formed by subglacial erosion of the mafic granulite of the Ivrea-Verbano Zone (Forno et al., 2005b, 2007). These hills represent the threshold of a glacial excavation hollow (Fig. 5), cut by the Dora Baltea glacier into the fractured rocks of the Canavese Zone and reaching a depth below sea level (at least -20 m), as documented by the 270 m deep core of Montalto Dora (3 in Fig. 4; Forno et al., 2010).

The <u>internal plain</u> is the most characteristic element of the IMA, because other end moraine systems have their internal depressions occupied by a big lake and/or low moraines while the plain is subordinated. The IMA internal depression is instead formed by a very wide fluvial plain distributed at two altitudinal levels: the alluvial plain and a series of fluvial terraces. The present alluvial plain, crossed by the Dora Baltea and Chiusella rivers, extends for 23 km in NNW-SSE direction throughout the inner basin from 250 m to 215 m a.s.l. and reaches a maximum length of 4 km. It is divided into two lowlands separated by the rocky Ivrea Hills, an obstacle that the Dora Baltea River crosses through a gorge at Ivrea (*Ponte Vecchio*). The fluvial terraces are distributed all around the alluvial plain at heights of not more than 15 m higher than the lowlands.

The <u>external outwash plain</u> is a high terraced proglacial sandur formed by a sequence of laterally interfingering glaciofluvial fans, each one originating from a different passage (spillway or *sfioratore*) across the moraine arcs (Fig. 4). On the apical portion of the glaciofluvial fans the traces connected with the ancient mining activities for gold are still visible (Gianotti, 2011). They are particularly evident in the Bessa aurifodinae in the IMA north-eastern sector (Baio & Gianotti, 1996). The main plain, linked to glaciofluvial activity during the two Serra expansions, is suspended up to 60 m above the present -day Dora Baltea riverbed. In more distal positions several higher terraces are suspended up to 10 m over the main plain, corresponding to the terraced relicts of more

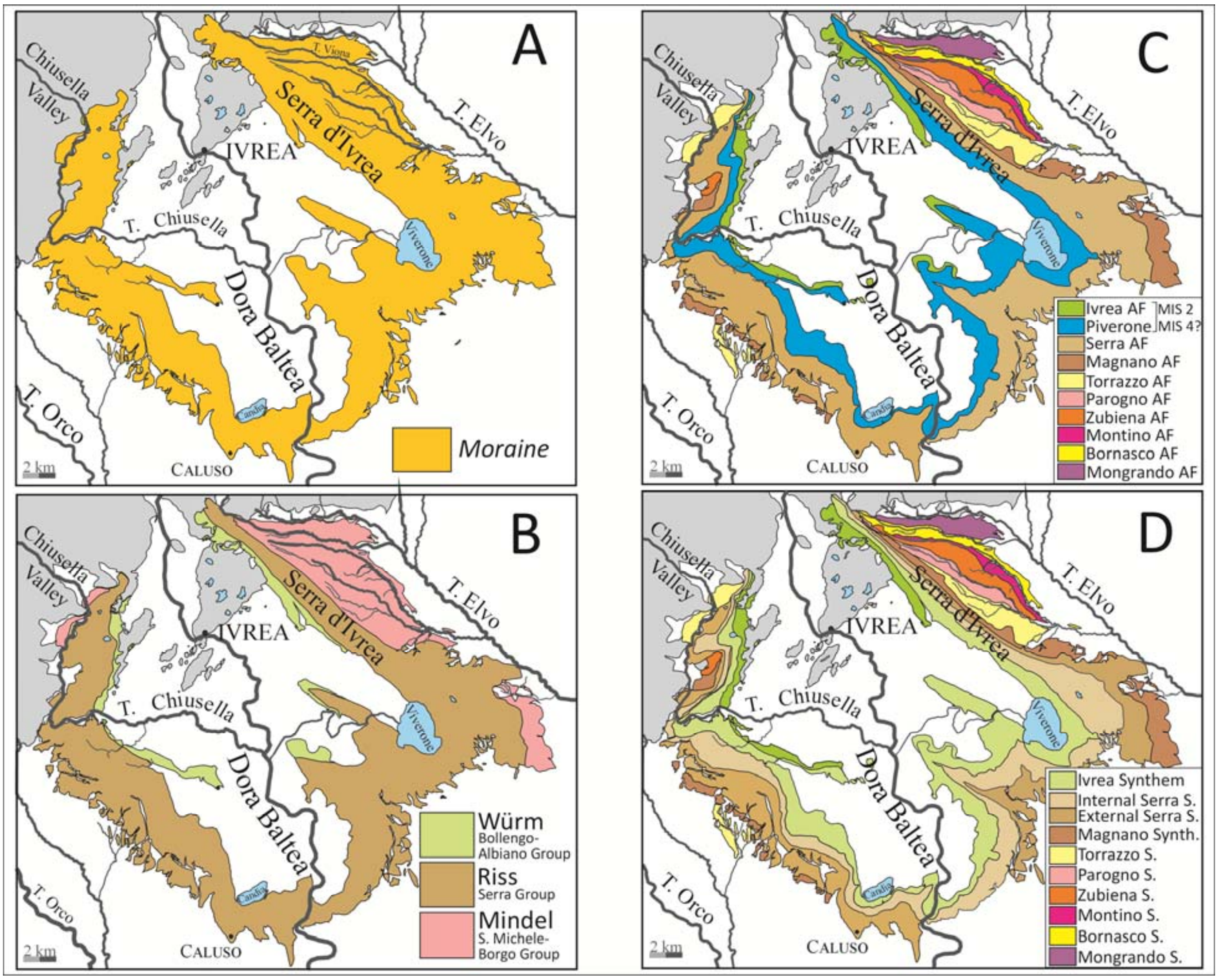


Fig. 6 - The stratigraphic mapping of the IMA according to different models on glaciations. (A) Only one long glaciation model (second part of XIX century). (B) Four glaciations separated by long interglacials according to Penck & Brückner (1894-1980ss). (C) Many glaciations separated by short interglacials (end of 20th century-Present). (D) Nine glaciations of the present work.

ancient sandur (between San Giusto, Foglizzo and Montanaro, at Torrazza, between Salussola and Carisio). The oldest terraces are covered by several layers of aeolian silt (loess), deposited during subsequent glaciations, and each weathered to a soil. This loess-palaeosol sequence has a thickness of some metres and is visible in abandoned quarries that used to exploit the clayey silt for pottery production. The distal sector of the outwash plain was very affected by the Pleistocene tectonic deformation involved in the uplift of the Collina di Torino and Monferrato hills and in the north and northwestern migration of their external margin (De La Pierre et al., 2003; Giraudi, 2014), as recognized in the westernmost Collina di Torino area (Forno & Lucchesi, 2005).

4. HISTORICAL BACKGROUND

The long history of study of the IMA can be well ordered by grouping its vast geological literature on the basis of the climate-stratigraphical model followed by the scholars. Following diffusion of the Glacial Theory (Agassiz, 1840), Studer (1844) recognized the glacial nature of the Serra d'Ivrea.

The IMA and the Rivoli-Avigliana amphitheatres were the first end moraine system studied in Italy (Martins & Gastaldi, 1850). In the surveys by Gastaldi and Bruno (Bruno, 1877), synthesized in the 1:400,000 Western Alps Map (Franchi et al., 1908), the IMA was regarded as an undifferentiated landform constructed during only a single glaciation (Fig. 6A). The glacial deposits (*deposito morenico*) were distinguished from Pliocene sediments, outwash sediments (*diluvium*) and postglacial fluvial sediments (*alluvium*). Baretti (1877) and Sacco (1888) also supported the single glaciation model. According to the Drift Theory of Lyell (1833), Bruno (1877) sustained a glacial-marine genesis of the amphitheatre when the sea still extended into the Alpine piedmont sector. He based his opinion on the diffusion of outcrops of well stratified fine sediments containing both dropstones and marine mollusc fossils, interpreted as glaciomarine deposits (at Sento and Pian Torinetto in the Strambinello LS, into the Rio Borriana stream incision, at Candia, Mazzé and Borgomasino in the Vische LS). This hypothesis was sustained by Stoppani (1880), but strongly denied by Baretti (1877), Sacco (1888) and Marco (1892), who considered the fossils as reworked.

Subsequently, Penck et al. (1894) and Penck & Brückner (1909) distinguished two Alpine glaciations (Y and Z glaciations or Riss and Würm, respectively) of their classical stratigraphy and considered the Serra d'Ivrea to be the largest morainic ridge in the Alps (**Fig. 6B**). The model of numerous glaciations was used in the first edition of the "Ivrea" sheet (Franchi et al., 1912) and in the "Biella" sheet (Franchi & Stella, 1933) of the Geological Map of Italy (1:100 000 scale). The proximal moraines in the Serra d'Ivrea were mapped as Würmian and the more distal moraines as pre-Würmian. Sacco (1927) distinguished three glaciations, tentatively correlated with Penck & Brückner's Mindel, Riss, and Würm glaciations, but with different limits with respect to the cross section of the Serra d'Ivrea proposed by Penck. Sacco (1927) considered the Serra d'Ivrea as a Rissian moraine. The Sacco subdivisions were followed in the second edition of the 1:100 000 sheet 43 "Biella" (Bortolami et al., 1966) and substantially confirmed in some synthesis publications (Carraro & Petrucci, 1969; Carraro et al., 1975). The IMA map in Carraro et al. (1975), which distinguishes the glacigenic sequence by facies and climate-stratigraphical units, was the most detailed map of the IMA until few years ago.

The issue on the glaciomarine origin was renewed with bio-stratigraphical work (Carraro et al., 1974, Barbieri et al., 1974; Cerchio, 1980) supporting the existence of the glaciomarine deposits in the Strambinello LS, based on: lithofacies analogy with the glaciomarine deposits described in literature, evidence of stratigraphical continuity with the underlying marine sediments, *in situ* oligotypical fossil fauna content, nonexistence of reworking proved by micro-foraminifer assemblages that are completely different from those of the marine sediments from which they should come, palynological content with non-reworked Tertiary elements attesting a Pliocene age of the deposit. In contrast, Basilici et al. (1998) excluded a glaciomarine environment for this unit, owing to the very different altitudinal distribution of its basal erosional surface and because they consider the paleontological content as reworked. A synthesis of this complex question is also reported by Carraro (in Martinetto, 1998).

According to the multi-glaciation model derived from the marine and ice-core isotopic stratigraphies (Emiliani, 1955; Shackleton, 1967; Shackleton & Opdyke, 1973) and following the criticism from various authors (i.e., Kukla, 1977; Bowen, 1978; Sibrava et al., 1986), the Penck & Brückner classical Alpine climate-stratigraphy was gradually abandoned in Italy and Switzerland (Schlüchter, 2004).

The IMA deposits were subsequently subdivided into three main allogroups (Carraro et al., 1991; Carraro, 1992), on the base of pedostratigraphy and morphology (Fig. 6B). The outermost San Michele-Borgo group included the ancient very weathered sediments preserved in the outer areas of the left side of the IMA. The intermediate Serra d'Ivrea group included most of lateral and frontal morainic ridges. The innermost Bollengo-Albiano group corresponded to relics of the more proximal morainic ridge (Piccola Serra and Strambino-Romano-Perosa moraines), referred to the LGM.

In the last decades the finding of interglacial/interstadial markers (palaeosols and lacustrine-palustrine layers interbedded within the glacigenic deposits) allowed recognition of ten stratigraphical units referred to as many glaciations (Fig. 6C; Gianotti, 1993, 1996, 2007; Baio & Gianotti, 1996; Gianotti et al., 2008; see the following sections for detail).

Geochronologic data obtained by palaeomagnetic (Carraro et al., 1991), radiocarbon (Schneider, 1978;

Arobba et al. 1997) and cosmogenic nuclide (Gianotti et al., 2008) dating methods, and the biostratigraphic data consisting of a reduced set of pollinic spectra (Schneider, 1978; Arobba et al., 1997; Gianotti & Pini, 2011) are presented in section 7 and used to constrain an updated stratigraphic reconstruction (Fig. 6D).

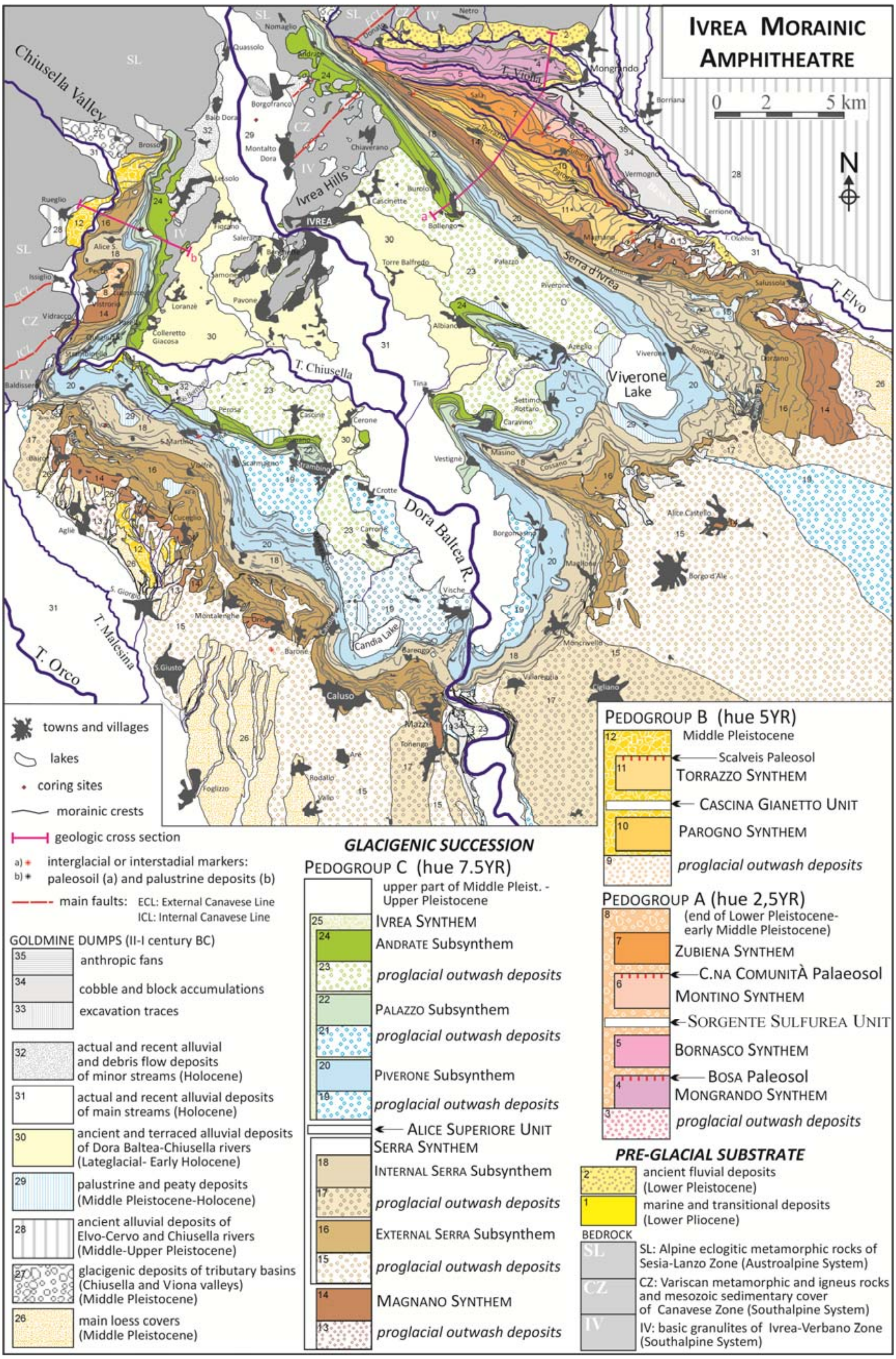
5. STRATIGRAPHY OF THE IMA

The onset of the Alpine Quaternary glaciation on the southern Alpine forelands was established at the end of the Early Pleistocene (Muttoni et al., 2003, 2007) with correspondence to global cooling of MIS22. The record of the glaciations is discontinuous along the southern side of the Alps and the IMA represents the end moraine systems with consistent differentiation of several glacial units (Fig. 7) that can be essentially linked to the different glacial stadials (from MIS 22-20 to MIS 2) of the global isotopic curve (Lisieki & Raymo, 2005).

The oldest glacigenic succession originated at the end of the Early Pleistocene according to the reverse magnetization of glaciolacustrine deposits covered by subglacial till at Mongrando (Carraro et al., 1991). Age and distribution of the innermost glacigenic succession is constrained to the LGM by radiocarbon and cosmogenic nuclide dating (Schneider, 1978; Arobba et al., 1997; Gianotti et al., 2008). Between these two outermost and innermost units, seven other glacigenic units have been distinguished (Gianotti et al., 2008), which for the most part must be referred to the Middle Pleistocene glaciations.

Before 2007, about 80% of the IMA was ascribed to two single sequences of glacigenic deposits of Middle Pleistocene age (san Michele-Borgo group, formerly Mindel, and Serra d'Ivrea group, formerly Riss), while only the remaining 20% was referred to the Late Pleistocene (the innermost Bollengo-Albiano group) (Carraro, 1992) (Fig. 6B).

Successively the San Michele-Borgo group was split into six alloformations (Mongrando, Bornasco, Montino, Zubiena, Parogno, Torrazzo) and the Serra d'Ivrea group into three alloformations (Magnano, Serra, Piverone) (Gianotti, 2003, 2005, 2007). In particular the innermost Piverone alloformation was distinguished from the Serra d'Ivrea group and ascribed to the Last Glacial Cycle (MIS 4 or MIS 2) of Late Pleistocene age (Gianotti et al., 2008). So the IMA area referred to the Late Pleistocene glaciation extended to more than half of the total extent of the morainic system (Fig. 6C). In the present


IVREA MORAINIC AMPHITHEATRE
0 2 5 km
N
Chiusella Valley
Ivrea Hills
IVREA
Serra d'Ivrea
T. Viona
T. Elvo
T. Chiusella
Viverone Lake
Dora Baltea R.
Candia Lake
T. Malesina
T. Orco
towns and villages
lakes
coring sites
morainic crests
geologic cross section
a) b) interglacial or interstadial markers: paleosoil (a) and palustrine deposits (b)
main faults: ECL: External Canavese Line
ICL: Internal Canavese Line
GOLDMINE DUMPS (II-I century BC)
35 anthropic fans
34 cobble and block accumulations
33 excavation traces
32 actual and recent alluvial and debris flow deposits of minor streams (Holocene)
31 actual and recent alluvial deposits of main streams (Holocene)
30 ancient and terraced alluvial deposits of Dora Baltea-Chiusella rivers (Lateglacial- Early Holocene)
29 palustrine and peaty deposits (Middle Pleistocene-Holocene)
28 ancient alluvial deposits of Elvo-Cervo and Chiusella rivers (Middle-Upper Pleistocene)
27 glacigenic deposits of tributary basins (Chiusella and Viona valleys) (Middle Pleistocene)
26 main loess covers (Middle Pleistocene)
GLACIGENIC SUCCESSION
PEDOGROUP C (hue 7.5YR)
upper part of Middle Pleist. - Upper Pleistocene
25 IVREA SYNTHEM
24 ANDRATE Subsynthem
23 proglacial outwash deposits
22 PALAZZO Subsynthem
21 proglacial outwash deposits
20 PIVERONE Subsynthem
19 proglacial outwash deposits
ALICE SUPERIORE UNIT
SERRA SYNTHEM
18 INTERNAL SERRA Subsynthem
17 proglacial outwash deposits
16 EXTERNAL SERRA Subsynthem
15 proglacial outwash deposits
14 MAGNANO SYNTHEM
13 proglacial outwash deposits
PEDOGROUP B (hue 5YR)
12 Middle Pleistocene
Scalveis Paleosol
11 TORRAZZO SYNTHEM
CASCINA GIANETTO UNIT
10 PAROGNO SYNTHEM
9 proglacial outwash deposits
PEDOGROUP A (hue 2,5YR)
8 (end of Lower Pleistocene- early Middle Pleistocene)
7 ZUBIENA SYNTHEM
C.NA COMUNITÀ Palaeosol
6 MONTINO SYNTHEM
SORGENTE SULFUREA UNIT
5 BORNASCO SYNTHEM
Bosa Paleosol
4 MONGRANDO SYNTHEM
3 proglacial outwash deposits
PRE-GLACIAL SUBSTRATE
2 ancient fluvial deposits (Lower Pleistocene)
1 marine and transitional deposits (Lower Pliocene)
BEDROCK
SL: Alpine eclogitic metamorphic rocks of Sesia-Lanzo Zone (Austroalpine System)
CZ: Variscan metamorphic and igneous rocks and mesozoic sedimentary cover of Canavese Zone (Southalpine System)
IV: basic granulites of Ivrea-Verbano Zone (Southalpine System)

work the Piverone unit is re-interpreted as the outermost, first subsynthem of the LGM succession (Ivrea synthem) and so referred to the maximum glacial expansion of the glacier during the MIS 2 glacial.

This stratigraphical reconstruction was based essentially on two items: the presence of interglacial/interstadial marker layers between the glacigenic sequences and the pedostratigraphical analysis. The used markers correspond to temperate-warm climate palustrine deposits or to evolved palaeosols, covered by subglacial or ice-marginal till. Both types of buried layers indicate long intervals of temperate-warm climate with interstadial or interglacial conditions. They separate deposits linked to glacial expansions with considerable difference in age, ranging from a few tens of thousands of years to about a hundred thousand years, respectively. Thus these layers correspond to discontinuity of range high enough to separate distinct synthems (see section 8).

Pedostratigraphy has also been utilized as a tool for stratigraphical subdivision. It must be said that, as detailed pedological studies were never performed in the IMA, soil data are somewhat rough. Vetusols on moraines are rarely visible in outcrop, are deeply eroded to various degrees and show at best only the remnants of a B-horizon. Not-significant inceptisols are dominant on the morainic relief. However, the evaluation of the color of surficial soils and derived colluvium, by using the Munsell Soil Colour Chart, has led to the rough recognition of three pedogroups characterized by different maximum hue index color: an older pedogroup A with a 2.5YR hue, an intermediate pedogroup B with a 5YR hue and a younger pedogroup C with a 7.5YR hue (Gianotti, 2007). The pedogroups A and B approximately coincide with the Mindel/San Michele-Borgo group, while the pedogroup C comprises the Riss/Serra group and the Würm/Bollengo-Albiano group units. This basic subdivision allowed separation of the oldest succession into two parts (in detail the Zubiena from the Parogno synthems). In addition, a different degree of weathering of the tills was crucial to distinguish the Magnano from the Serra synthems, two units of the same pedogroup C.

The most recent Ivrea synthem was further subdivided on morpho-stratigraphical basis into subsynthems, which correspond to the LGM and Lateglacial stadials of the last glaciation. The term stadial is here referred to the classical Alpine climatostratigraphy concerning the phases of the glacial retreat (reference in Ivy-Ochs and al., 2008). In principle, each synthem could be further split into subsynthems, each referred to different glacial readvance with hundred/a few thousand of years of age gap (each morainic circle being a subsynthem). However, only the latest synthem may retain a complete set of recessional moraines.

A complete sequence of the until now recognized stratigraphical units is described below, using the synthem terminology according to the U.B.S.U. stratigraphy used into the new Geologic Map of Italy at the 1:50,000 scale (Salvador, 1994; Carraro et al., 2012).

5.1. The Mongrando synthem

The oldest glacigenic deposits of the amphitheatre form the outermost moraines in the northeastern sector of the IMA (unit 4 in Fig. 7). They consist of a group of three juxtaposed moraines stretching in a W-E direction between Donato (1 in Fig. 8) and Mongrando and delimited by the fluvial incisions of the Ingagna and Viona streams on the north and on the south respectively. Thus the Ingagna stream marks also the outer boundary of the IMA in this sector (b in Fig. 8).

These moraines show an abrupt termination towards the east above the Mongrando village, where they were cut off by erosion by the Ingagna and Viona streams (a in Fig. 4). A past extension of this morainic circle can be hypothesized on geometric relations toward the SE in a flat area (the Biellese alluvial plain) where the Elvo-Cervo fluvial fan develops. A group of large boulders of eclogitic micascists in the Elvo riverbed near the Borriana village, resting on the Lower Pliocene marine sediments, are present. Because of their size and position they can be interpreted as erratic blocks, so their presence support a former wider extent of the amphitheatre towards the plain of Biella 1.8 km beyond its current boundary.

Most of the outcropping sediments are interpretable as subglacial melt-out till and lodgement till also forming the upper part of the morainic relief. The long lasting erosion has exhumed the pre-glacial substrate now forming the lower part of the morainic relief in its easternmost sector (Mongrando), made up of deeply weathered pre-glacial fluvial sandy gravels linked to the local basins (palaeo-Elvo). The ancient fluvial deposits rest on the basic granulites outcropping in the Ingagna valley floor. Southward, the widespread subglacial till in the Viona riverbed represents the innermost outcropping deposits of this unit. It consist of a strongly overconsolidated matrix-supported diamicton ranging from a massive and fissile lodgment till to a poorly stratified melt-out till, often deformed into staked slices by glaciotectonism, unweathered and so with a homogeneous pale blue-grey color. Near Cascina Balca, NW of Bornasco, the subglacial till frequently includes macro-remains of trees (branches, small trunks, roots) yet to be studied. Very thick vetusols are locally visible on the morainic crests, where sporadic limbs of marginal flow till are preserved. They are deeply weathered, reaching a red color with a hue of 2.5YR that corresponds to the most developed soil profile of the IMA.

Starting with Penck et al. (1894) all authors agreed to assign these external moraines to the oldest glaciation recognizable in the IMA which, however, according to Penck et al. (1894) and Penck & Brückner (1909) is the penultimate glaciation (Y or Riss). Later, these mo-

Fig. 7 - Geologic map of the Ivrea Morainic Amphitheatre. Pedostratigraphic groups are indicated and further subdivided into nine synthems attributed to different glaciations, based on the presence of interbedded interstadial or interglacial markers or by pedostratigraphy. Serra synthem (MIS 6 glacial) and Ivrea synthem (MIS 2) are further subdivided into subsynthems on morphological basis (updated from Gianotti et al., 2008).

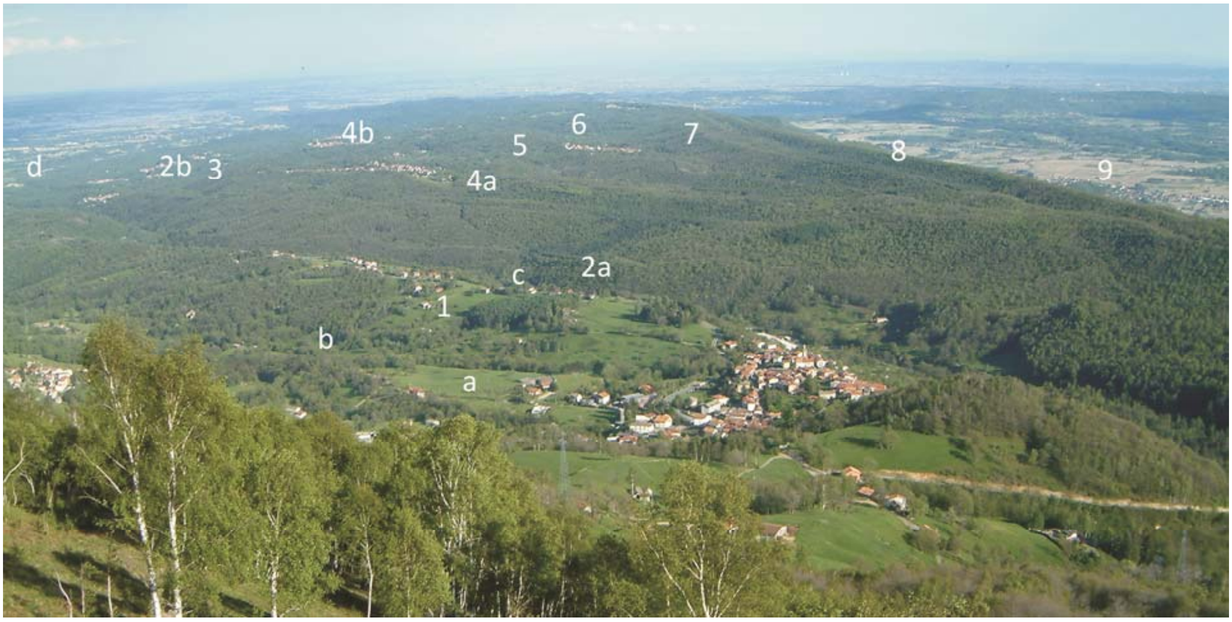


Fig. 8 - Panoramic view of the north-eastern sector of the IMA (from the Bric Paglie slope at 1200 m a.s.l.). The terraced high plain of Donato (a) is part of the local pre-glacial units named *altopiani villafranchiani*. The Ingagna stream incision (b) and the Elvo River alluvial plain (d) mark the IMA northeastern and eastern edges respectively. The Donato-Mongrando moraine (1) is the oldest of the IMA; the Bosa palaeosol into the Viona stream incision (c) separates this moraine from the innermost Bornasco unit (2a), that downstream forms the Bornasco-Vermogno moraine (2b). The low moraines of the Montino synthem (3) are scarcely visible. The Sala Biellese (4a) and Zubiena (4b) villages lie above the higher crests of the Zubiena synthem. The moraines of the Parogno (5), Torrazzo (6), Magnano (7) and Serra (8) follow inward. In the internal depression the Piccola Serra moraine (9) just overlooks.

raines were referred to the Mindel glaciation by Sacco (1927), Gabert (1962), Carraro & Petrucci (1962), Carraro et al. (1975) and in the first and second editions of the Biella Sheet of the Geological Map of Italy (Franchi & Stella, 1933; Bortolami et al., 1966, respectively). Carraro et al. (1991) carried out a palaeomagnetic analysis of a glacigenic sequence composed by two glaciolacustrine bodies, referred to glacier advance and retreat phases respectively, separated by subglacial till (San Michele-Borgo unit) at the eastern edge of the Mongrando moraine (Rio Tenerello). A reverse polarity was registered in the lower lacustrine succession (Granero unit) and a normal polarity into the upper one (Castello unit). This result allowed to assign the first evidence of glaciation in the IMA to the Lower Pleistocene - Middle Pleistocene boundary, actually placed at 780 ka BP following Gibbard et al. (2005). Later the name of San Michele-Borgo group was extended to include all the IMA Mindel moraines (Carraro, 1992) and the glacial deposits of the Donato-Mongando moraines were renamed as Mongrando alloformation (Gianotti, 1993, 1995).

5.2. The Bosa palaeosol

In the NW sector of the IMA weathered colluvial deposits crop out at the bottom of the T. Viona incision at SE of Case Bosa near the village of Donato (c in Fig. 8). The 2.5 m thick colluvial deposits correspond to matrix-supported, apparently massive, weakly gravelly silty-sands, coming from the resedimentation of glacial deposits. This colluvial cover lies on a marginal flow till, visible at the base of the small outcrop, made of coarse gravel and silty sand and poorly clino-stratified (immerging N25/30, i.e. towards the external edge). At the top the colluvium is covered by a more than 2 m thick fluvial deposit forming the Viona alluvial plain. In the riverbed a typical subglacial till frequently crops out, likely forming the basal layer of the described sequence.

The colluvial deposits and the underlying marginal flow till are weathered by pedogenesis through their full thickness. This soil is cut off at the top and it is the remnant of a B-horizon, with clay illuviation, moderate pedogenic aggregates, large Mn oxide mottles and thin discontinuous pseudogleys. The hue color index of the matrix does not exceed a 7.5 YR value. The few clasts are all deeply weathered. The weathered colluvial deposits are strongly overconsolidated, because they are much more cohesive and harder than you would expect from cementation by oxides linked to pedogenesis. The over-consolidation can instead be explained by the pressure of the glacier during a subsequent advance (post-pedogenesis) past the present Viona incision, but not so far off as to completely erode the soil.

This condition allows using the soil as a stratigraphical marker separating the products of two distinct glaciations preserved North of T. Viona incision. According to this reconstruction, the soil was formed in the colluvial cover of a marginal till forming a stadial moraine of the Mongrando synthem (first glaciation). The pedogenesis proceeded particularly during the first subsequent interglacial. Subsequently this soil was overridden and consolidated by the Dora Baltea glacier and probably buried by subglacial deposits during a later glaciation (Bornasco), likely already during the Middle Pleistocene as suggested by the presence of the glaciolacustrine deposits with normal magnetic polarity at Mongrando (Castello unit in Carraro et al., 1991). The ice marginal position reached by this advance can be tentatively identified at least with the first moraine that lies downstream of the Viona stream, corresponding to the small lateral moraine of Bosa, which extends just beyond the incision. Thus, the Bosa moraine marks the maximum glacier extent during the Bornasco glaciation (see 5.3) The involved soil can be defined as a palaeosol, referring to its recent alluvial cover, but mainly as an exhumed soil, since it derives from an ancient palaeosol whose sedimentary cover was removed.

5.3. Bornasco synthem

The Bornasco synthem has a restricted distribution at the outer edge of the NE sector of the IMA and includes the glacigenic deposits attributed to the second glaciation distinguished in the IMA (unit 5 in Fig. 7). These form a moraine group, which runs for about 15 km in length and less than 1 km in width, between the Viona and Olobbia streams, with the exception of the Bosa moraine that is beyond the Viona (see 5.2). To the north these moraines are surrounded by the Mongrando moraines; to the south-east, between Mongrando and Cerrione villages the main Bornasco-Vermogno lateral moraine is itself the outermost preserved moraine, as the Mongrando synthem deposits have been completely removed by fluvial erosion in the Bessa area. The same Bornasco-Vermogno moraine is the only morphological remnant of a previous complex covering an area of over 10 km^2, now forming a high fluvial terrace buried and surrounded by the impressive tailings of an ancient Roman gold mine (the Bessa *aurifodinae;* Fig. 7). The gold placer was likely formed by poly-phased fluvial erosion (Viona and Olobbia streams) and re-sedimentation of the previous glacigenic deposits of the Bornasco synthem. The previous existence of a till cover is documented by the presence of many erratic boulders in the Bessa mine dumps.

The Bornasco synthem glacigenic deposits, up to 75 m thick (at Fontanile near Donato), rest on bedrock south of Donato village or against the Mongrando till north of the Viona stream. In the Bessa area they directly overlie the deeply weathered fluvial sandy gravel forming the pre-glacial substrate (Lower Pleistocene Elvo and Dora Baltea alluvial fans). The upper surface of these moraines, trending from 660 m to 310 m a.s.l. in elevation, is deeply weathered as documented by strongly evolved vetusols with a 2.5YR hue, thick at least up to 2.5 m and with completely altered clasts. Even in this case the soils are more or less strongly truncated.

The Bornasco synthem is characterized also by a high diffusion of very fine marginal glaciolacustrine deposits in its southeastern sector, particularly outcropping along the Olobbia riverbed. They are sands and weakly gravelly silty-sands, well stratified but deformed by glaciotectonism (folds), of a typical yellow color for the middle sand layers (turbiditic supply) and pale-yellowish grey for the massive diamicton layers (corresponding to aquatic flow till or to gravitative flow sediments). Some silty-sandy layers contain fragments of *Chlamys* sp., *Modiolus* sp. and internal and external molds of marine bivalves. The fossils belong to Lower Pliocene (Zanclean) faunas typical of a marine sandy sedimentary environment, but they are broken and abraded and so they are clearly reworked (Gianotti, 1993). The perfect stratification and lamination of these yellow sands persuaded Sacco (1927a, 1927b) to consider them as Upper Pliocene deposits in facies *maremmana* i.e. transitional. They were likely only supplied by glacial erosion and re-sedimentation of the marine sandy substrate, as the texture and the fossil content suggest. At the basis of the succession a thin layer of lodgement till passing to a thicker subglacial melt-out till into the Riale della Valle stream waterbed is found. This till covers a palaeosol formed at the top of fluvial gravels forming the preglacial substrate. Only at the top of the succession are marginal flow till and marginal glaciofluvial gravels preserved on the moraine crests, with thickness increasing upstream (NW of Briengo). The external moraine parallel to the moraine on which the Bornasco village lies is constituted at the top by deformation till, made of slices of diamicton corresponding to previous subglacial melt-out till.

The Bornasco moraines were attributed to the same glaciation as the Mongrando moraines, i.e. to the Riss by Penck & Brückner (1909) and to the Mindel by Sacco (1927). The Bornasco synthem, belonging to the San Michele-Borgo group (Carraro, 1992), was distinguished in the Bessa region on morpho-, litho-, and pedostratigraphic basis and referred to the lower part of the Middle Pleistocene (Gianotti, 1993, 1996; Baio and Gianotti, 1996).

The Bornasco synthem can be separated from the outermost Mongrando synthem by the Bosa exhumed palaeosol and from the innermost Montino synthem thanks to the interglacial peat layer of Sorgente Solfurea. Furthermore, it is distinguished from the Montino synthem by a higher degree of weathering: soils appear thicker on the Bornasco moraines, which frequently reach 2.5YR hue color indices, while the Montino moraines are characterized by the conservation of palaeosols with a 5YR hue (but see 5.5).

5.4. Sorgente Solfurea interglacial layer

This unit separates the Bornasco synthem from the overlying Montino synthem and can be referred to an interglacial or interstadial phase. It is the most problematic unit of the IMA sequence, as the position of this significant layer is identified not so much from outcropping sediments, but from a water spring, named the Sorgente Solfurea (Sulphurous Spring), well known in the Biella and Canavese region for its healing properties. The spring is accessed by a drinking fountain next to a restaurant at the outlet of a tributary incision of the T. Olobbia. The water emerges at the contact between a not visible peat layer and an overlying fluvial-lacustrine complex formed by varicolored clayey sands, sands and gravels, cropping out between 350 and 370 m altitude. Therefore the upper permeable alluvial formation represents the aquifer of the water spring, while the peat layer represents its basal acquiclude.

The peats were intersected by a landslide scarp at 350 m a.s.l. into the incision flank, during an alluvial event in 1994, and many peat fragments were visible in the riverbed at that time. The peats rest on glaciolacustrine deposits of the Bornasco synthem, outcropping up to a level of 345 m a.s.l. in the bottom of the small incision next to the restaurant and extensively along the bed of the T. Olobbia.

Above the peat layer a 4-5 m thick lacustrine body of stratified clayey silts and silty sands crops out poorly. At the base, a layer of laminated clayey silts and silty sands containing numerous small vegetal macro remains is present. A sample from a clayey silt level had been subjected to palynological analysis (Gianotti, 1993). The pollen association indicates a coniferous forest of relatively cold climate, while the thermophilous elements are scarce or ambiguous (E. Martinetto, pers. comm.). *Cyperacea* and *Filicales monolete* may be in relation to a humid environment, but well drained according to the absence of *Concentrycistes* (Tab. 1).

These fine sediments are covered by glaciofluvial sandy gravels with well-rounded pebbles, and with the degree of weathering increasing upwards. The scarcity of outcrops does not allow to verify the continuity of this succession, reaching 375 m of elevation. The gravels switch at the top to marginal flow till and this is buried by subglacial melt-out till of the Montino synthem.

5.5. Montino synthem

The Montino synthem includes the glacigenic deposits linked to the third glacial advance registered in the IMA (unit 6 in Fig. 7). It forms a 11 km long group of low lateral moraines aligned along the T. Olobbia stream incision, but its extent is limited to a very thin band, of 200-300 m to 800 m near Montino, limited to the left (eastern) IMA sector: because most of the deposits were buried by the subsequent Zubiena synthem glacigenic deposits, the Montino synthem is the narrowest unit of the IMA. The deep incision of the T. Olobbia downstream Montino village marks the boundary between the Bornasco and Montino synthems.

The Montino moraines were initially referred to the Riss by Penck & Brückner (1909), to the Mindel by Sacco (1927) and later to the San Michele-Borgo group by Carraro (1992). Its glaciofluvial deposits, very widespread and thick in the southeastern sector (Montino-La Tana), together with the Cerrione unit (fluvial pre-glacial substrate), may correspond to the *Diluvium* of Sacco (1888). This glaciofluvial facies was interpreted as the basal and external part of the Zubiena synthem (Gianotti, 1993). The Montino synthem was finally differentiated by Gianotti (2007) on the basis of a palaeosol at the top of the glaciofluvial sequence (Cascina Comunità palaeosol, see 5.6).

Sorgente Solfurea section (Zubiena, BI)					
	n°	%		n°	%
Abies	3	2.2	Betula	2	1.4
Pinus	77	56.6	Alnus	1	0.7
Larix	1	0.7	Valeriana	1	0.7
Cupressaceae	26	19.1	Urticacea	5	3.7
Corylus	1	0.7	Cyperacea	5	3.7
Ostrya	2	1.4	Filicales monolete	12	8.8

Tab. 1 - List of pollen taxa detected only in one sample of the Sorgente Solfurea site, from a layer above the buried peat layer (outcrop in incision 50 m upstream of the Restaurant La Bessa, Zubiena). FPA = 6423 grains/g (from Gianotti, 1993).

The Montino synthem is characterized by glacio-aquatic deposits prevailing on the tills in the central sector, between Montino and Albare. On the right side of the Olobbia Valley and into its tributary incisions a 30 m thick sedimentary succession is visible in several wide outcrops: fluvial coarse gravels at the base, with well-rounded pebbles and cobbles; they are passing in continuity to a glaciolacustrine sequence. The coarsening upward sequence of the sandy gravel layers and the increase in the angularity of the clasts suggest the approach of the glacial front. But the presence of rhythmites in the middle-upper sequence indicates the persistence of a lake likely dammed by the glacier downstream. This aquatic succession is overlain by a boulder -rich deposit several meters thick, which corresponds to a marginal flow till. The weathering notably increases upward, passing from the unweathered basal gravels to deeply weathered clasts in the upper 10 m at the top of the succession.

The depositional surface at the top is weathered into reddish soils, which reach 2.5YR hue color index only in the weathered colluvial deposits that cover the morainic flanks in the northern sector. In turn, the moraines lack such evolved soils, because they are strongly truncated by erosion. In the southeastern sector (right side of the lower Olobbia valley) 2.5 m thick soils are frequent with a more than 1.5 m thick B-horizon with pedogenetic aggregates, hue 5 YR and deeply altered clasts. In the C-horizon the weathering front of the clasts reaches to almost 6-7 m in depth. These soils are much thicker and were preserved from erosion because they were buried by marginal tills of the subsequent glaciation (Zubiena synthem). Nevertheless further pedogenetic evolution was stopped by this burial, while a 2.5YR hue is frequently reached in soils of the overlying more internal and recent Zubiena synthem.

The Montino synthem is separated from the outermost Bornasco synthem by the Sorgente Solfurea interstadial peat layer and from the innermost Zubiena synthem by the Cascina Comunità palaeosol (5.6).

5.6. Cascina Comunità palaeosol

A palaeosol is present at the top of the Montino synthem and separates it from the overlying Zubiena synthem. North of Cascina Comunità (between Mongrando and Zubiena) two sequences of glaciolacustrine deposits crop out in the stream gully of a tributary of the T. Olobbia. This stream likely derives from a previous spillway of a Zubiena synthem frontal moraine. The lower unit (Montino synthem) is deeply weathered, with at the top traces of pedogenetic aggregates into coarse sands with a reddish 5YR 4/4 color and into silty fine sands with a yellowish brown 7.5YR 5/8 color. In comparison, the upper glacigenic sediments are greyish because they are unweathered, producing a strong color contrast at the contact between the two units. This upper unit is interpretable as a lacustrine sequence during the glacier advance, as the deposits are deformed and covered by a 20 m thick glacial deposit (not outcropping) forming a moraine referred to the Zubiena synthem.

About 350 m downstream (NNW of Montino) the lower glaciolacustrine unit presents an 80 cm thick pedogenized diamicton at the top, corresponding to an aquatic flow till. The unit is very coherent, with traces of pedogenetic aggregates, abundant Mn-oxide mottlling and a hue color of 5YR 5/8. Also this soil is buried by a thin body of unweathered stratified gravelly sands and by colluvial products deriving from the re-sedimentation of the Montino synthem weathered till during the subsequent glaciation.

Further to the south, at the southeastern edge of the Montino and Zubiena synthems near Cascina Cecco at 350 m a.s.l., another palaeosol crops out in the Rio della Valle Sorda riverbed (a tributary stream of the Olobbia stream). It separates two subglacial tills which are otherwise indistinguishable. The soil, developed at the top of subglacial deposits of the Montino synthem, depicts a flat palaeo-surface exposed after glacier withdrawal. The soil was successively buried by subglacial melt-out till during the successive glaciation (Zubiena synthem) and then finally exhumed. This stratigraphic reconstruction is supported by the plano-altimetric position of this succession and of their correlated ice-marginal landforms.

5.7. Zubiena synthem

The Zubiena synthem, together with the other ancient units, is only clearly recognizable in the northeastern sector of the IMA. It comprises glacigenic deposits referable to the fourth glaciation recognizable in the IMA (unit 7 in Fig. 7), well outcropping in the middle of the IMA left sector (4 in Fig. 8). They form an 11 km long and up to 1.4 km wide lateral morainic complex, the widest of the ancient units. It is externally bounded by the Olobbia stream and internally by the Valle Sorda stream.

The Zubiena moraines were referred to the Riss (Penck & Brückner, 1909), to the Mindel (Sacco, 1927) and finally grouped into the San Michele-Borgo group (Carraro, 1992). The Zubiena synthem was distinguished on a pedostratigraphic basis from the surrounding Bornasco and Parogno synthems (Gianotti, 2003), and later (Gianotti, 2007) also from the Montino synthem.

The basal contact which trends from 700 to 370 m a.s.l. is an erosional surface by which the Zubiena synthem lies above the Montino synthem and, only at the northwestern edge (south of Donato), directly above the Bornasco synthem. Outcrops of subglacial and marginal tills prevail.

The moraines, although deeply remodelled as their rounded crests show, appear very well expressed and with steep sides, having been only partially lowered by fluvial incision. The Sala Biellese (4a in Fig. 8) and Zubiena (4b in Fig. 8) villages lie above the two moraine alignments. The depositional top of the succession is characterized by red soils, more or less deeply cut by erosion, reach a hue color of 2.5YR and with deeply weathered clasts. The Zubiena synthem is part of the IMA most ancient 2.5YR pedogroup A.

The Zubiena synthem is separated from the outermost Montino synthem by the Comunità palaeosol (5.6), while the distinction with the innermost Parogno synthem (see 5.8) is exclusively pedostratigraphical, because the Zubiena synthem belongs to the pedogroup A and the Parogno synthem to the pedogroup B.

5.8. Parogno synthem

The Parogno synthem was clearly identified only in the left lateral IMA sector, while in the other sectors of the amphitheatre it could not be separated from the subsequent Torrazzo synthem, as they show a similar degree of weathering. This unit groups the glacigenic deposits related to the fifth glaciation recognizable in the IMA (unit 10 in Fig. 7). It was distinguished from the Zubiena synthem on the basis of pedostratigraphy by Gianotti (2003) into a very limited sector eastwards of Parogno. Before, the Parogno moraines were considered to be of Riss (Penck & Brückner, 1909), Mindel age (Sacco, 1927) and were later assigned to the San Michele-Borgo group (Carraro, 1992).

Four moraine alignments are recognizable, stretching 9 km long between the Scalveis and Parogno hamlets. This unit reaches its maximum width of 800 m and is roughly bounded by the Riale della Valle Sorda and Riale di Parogno stream incisions. The moraines are not very different from those of the surrounding units: they are well formed, sometimes continuous, with very rounded crests. At the south-eastern edge the ridges end abruptly above the Riale della Valle Sorda and Riale di Parogno streams confluence, because they are truncated by the intersection with the Torrazzo synthem. The depositional top of the succession is characterized by yellowish red soils, weakly preserved, reaching a 5YR hue color into the B-horizon of decimetric thickness and with deeply weathered clasts. The Parogno synthem is the first unit to return a clear and sustained color index lower than 2.5YR, typical of the outermost units. So it belongs to the intermediate 5 YR pedogroup B. The Parogno synthem is differentiated from the outermost Zubiena synthem owing to its less evolved soils (*hue* 5YR versus 2.5YR, respectively). It is separated from the innermost Torrazzo synthem by the Cascina Gianetto interglacial palustrine layer (see 5.9).

5.9. Cascina Gianetto palustrine gyttja layer

In the middle of the IMA left lateral sector a layer of gyttja was found (Marcuzzi, 2007; Gianotti, 2007) in a deep stream incision between the village of Parogno and Cascina Gianetto (Fig. 9B). It separates two sequences of glacigenic deposits, both correlatable to marginal tills characterized by soil colors of hue 5YR. The 80 cm thick gyttja layer rests on subglacial deposits constituted by lodgement and deformation till (with staked slices of glaciolacustrine deposits, Fig. 10D) referred to the Parogno synthem, forming moraines in outermost position, and is covered by a succession of subglacial and marginal glacigenic sediments referable to the Torrazzo synthem forming the overstanding moraines.

The pollen content of this layer (Gianotti & Pini, 2011) suggests a correlation with the MIS 11.3 and the MIS 9.3 interglacial phases (see 7).

5.10. Torrazzo synthem

The Torrazzo synthem can be recognized as a single unit only in the left lateral IMA sector. This unit includes the glacigenic deposits related to the sixth glaciation (unit 11 in Fig. 7). Also this morainic complex is part of the San Michele-Borgo group (Carraro, 1992), i.e. formerly Riss (Penck & Brückner, 1909) or Mindel (Sacco, 1927). It was stratigraphically distinguished thanks to the finding of an organic rich layer in a stream incision south of Parogno (Gianetto interstadial layer, 5.9).

The Torrazzo synthem is morphologically characterized by the large number of moraines in the IMA left sector, mainly in frontal position (6 in Fig. 8). Seven moraine alignments are recognizable, bounded by the Rio di Parogno - Riale della Valle Sorda incisions and stretching 11 km long between the Torrazzo and Cerrione villages with maximum width of 1.7 km NE of Magnano. The outermost moraines, on which the Torrazzo village lies, are straight lateral moraines. At Santo Sudario a wider frontal moraine complex developed, and this arrangement was maintained also by the innermost frontal moraines built during subsequent glaciations (Magnano and Serra): a small continuous, complete and well-preserved morainic amphitheatre resulted thanks to a progressive shifting of the glacier margin towards the south (6 in Fig. 4). East of Santo Sudario the Torrazzo Synthem ends because it is intersected and covered by the subsequent innermost Magnano synthem glacigenic deposits. The depositional top of the succession is characterized by eroded yellowish red soils with a maximum hue color of 5YR and containing deeply weathered clasts.

The Torrazzo synthem can be separated from the outermost Parogno synthem thanks to the occurrence of the Gianetto interglacial palustrine layer (5.9). It can be distinguished from the innermost Magnano synthem on pedostratigraphical basis as they belong to different pedogroups (*hue* 5YR versus 7.5YR, respectively).

The outermost morainic complexes in the western (right) IMA sectors, particularly in the Chiusella Valley and North of San Giorgio Canavese, are distinguished as 5YR pedogroup B, which comprises the undifferentiated Torrazzo and Parogno synthems. In the Chiusella Valley they form a notable morainic complex linked to a glacial lobe (Villa Riccardi LS) that passed over the watershed and came down to dam the Chiusella valley foot. Also in the frontal easternmost edge of the IMA a small strip of glacial deposits, on which the Salussola cemetery lies, is referable to the 5YR pedogroup owing to its higher degree of weathering and remodelling on respect to the innermost Magnano frontal moraines. Here a palaeosol outcrops, buried by 2 m thick fine sediments interpretable as the proglacial outwash deposits of the subsequent Magnano phases. This soil shows pedogenetic aggregates, marked Mn-oxides mottles and nodules and a 10YR 5/4 hue color with some mottles up to 7.5YR 5/8.

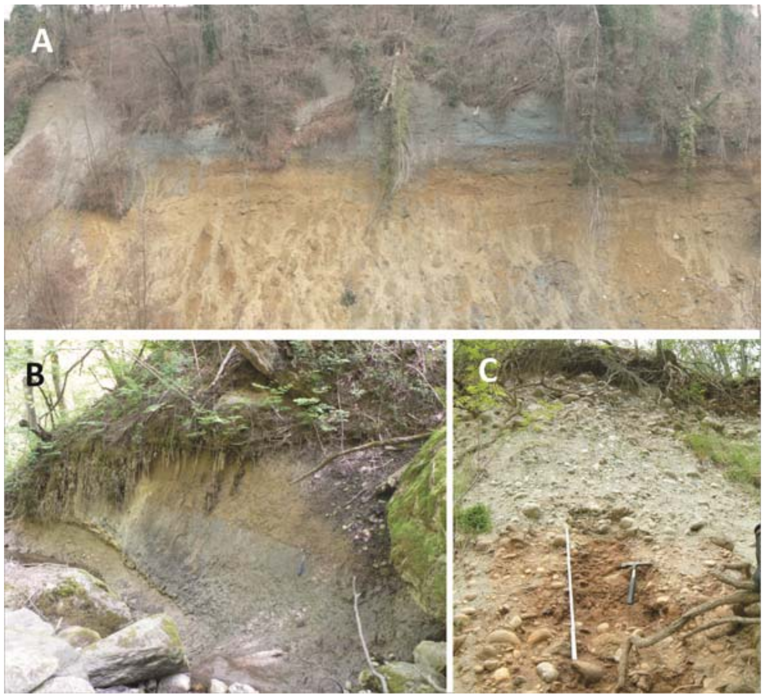


Fig. 9 - Photos of interglacial markers in the IMA. (A) Rio Rudo palaeosol well-exposed in the right side of the Rio Rudo incision, separating the Serra subglacial till (below) from the Ivrea subglacial melt-out till (above). (B) Glaciotectonized Cascina Gianetto gyttja layer separating the Parogno subglacial till (below) from the Torrazzo glacigenic sequence (above). (C) Glaciofluvial gravel of the Piverone subsynthem (LGM) resting above a weathered glaciofluvial gravel of the pedogroup B (Torrazzo or Parogno synthems) (abandoned quarry near Mazzé).

5.11. Pré palaeosol

Southeastwards of Scalveis a frontal complex built by a small lobe classified to the Magnano synthem (see 6.12) surrounds a small depression hosting the ephemeral Pré Lake. In this sector the Magnano moraines intersect the Parogno moraines (Fig. 7). The till forming the frontal arc buries a palaeosol at 685 m a.s.l. which formed at the top of the Parogno glacigenic deposits. It shows moderate pedogenetic aggregates and a strong brown 7.5YR 5/6 hue color with wide dark reddish brown 2.5 YR 3/4 mottles.

5.12. Magnano synthem

The Magnano synthem roughly corresponds to the outermost and ancient sector of the Serra d'Ivrea group (Carraro, 1992). This unit includes the glacigenic deposits referable to the seventh glaciation (unit 14 in Fig. 7). The Magnano synthem is the first unit (in chronological order) to show a significant distribution and extent in all the IMA sectors, with the exception of the southeastern frontal sector (between the Dora Baltea incision and Cavaglià), where it is not preserved. Moreover, the outermost border of the IMA frontal sector is reached by the Magnano moraines, which go up to 1.5 km (east of Cavaglià) or several hundred meters (between Bairo and Cuceglio; at Orio; at Mazzé) beyond the position of

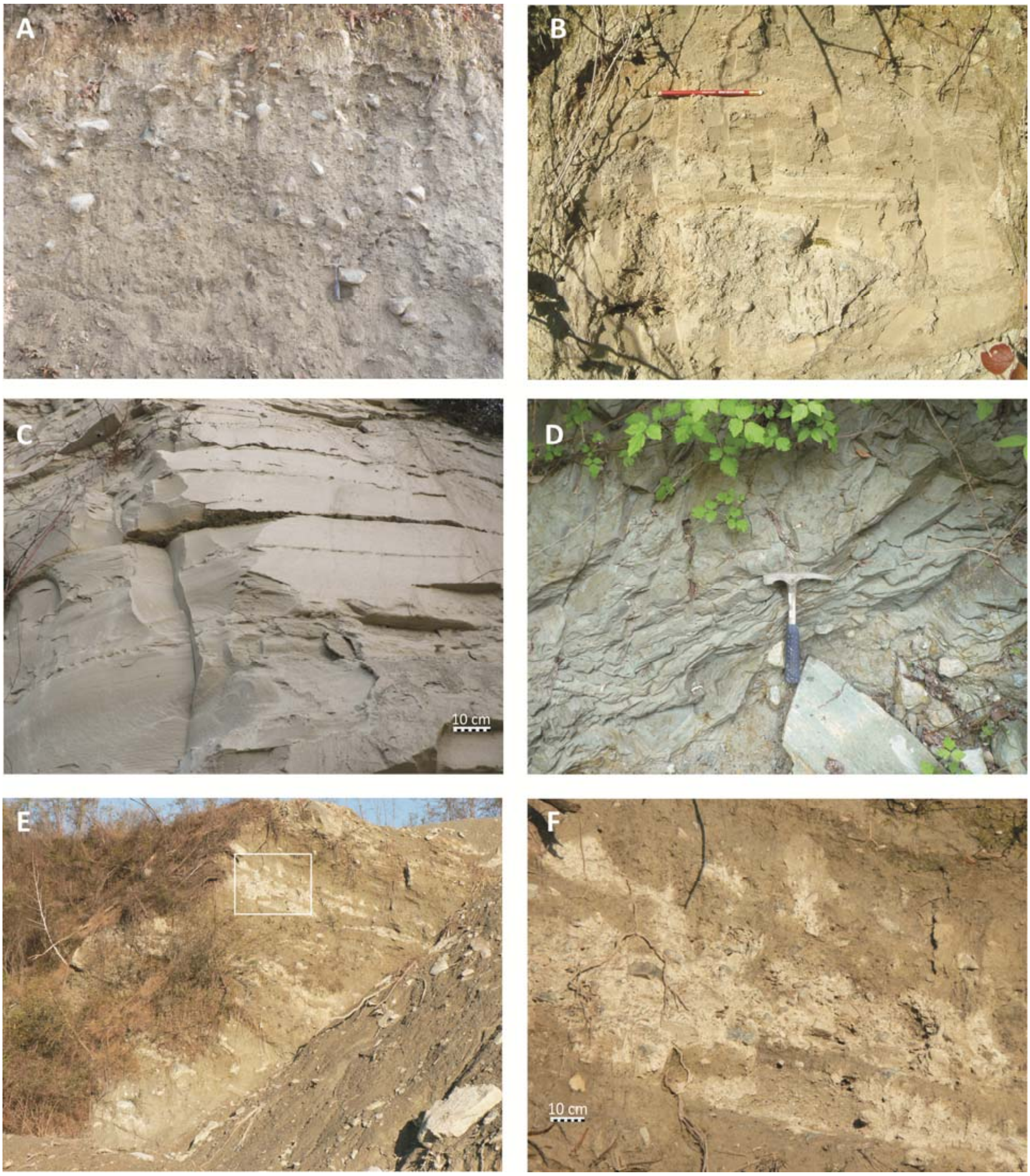


Fig. 10 - Different facies of glacigenic deposits cropping out in the IMA. (A) Lodgement till of the Internal Serra subsynthem (Palazzo). (B) Submarginal melt-out till forming the M. Bicocca frontal moraine, referred to the External Serra subsynthem (Mazzé). (C) Proglacial glaciolacustrine bottomset deposits of the Piverone subsynthem, made of parallel-laminated sandy silt (Dora Baltea R. left side, Cascine Francia, SE of Vische). (D) Slices of proglacial glaciolacustrine clayey silt resulted from subglacial thrusting during the Torrazzo glacial expansion (Riale di Parogno creek near Cascina Gianetto, Magnano). (E-F) Submarginal melt-out till forming the Parella frontal moraine truncated by the Chiusella R. incision (Andrate subsynthem, South of Parella). Note the up-glacier dipping stratified sediments conforming to the inner slope of the moraine (E). The white box indicates the detail of the diamicton shown in F.

the Serra moraines. Taking into account its glacial margin extent, the Magnano synthem can justly represent the MEG (most extensive glaciation) for the Dora Baltea basin.

In the IMA eastern sector this unit comprises four main moraine alignments (7 in Fig 8), stretching for 25 km between Castel Rubino (Andrate) and the Cavaglià village. The 1.7 km maximum width is attained at its southeastern edge at Cavaglià, but it extends also in the area of the San Sudario LS North of Zimone. A series of small LSs defined by the outer moraine are to be highlighted, such as those encircling the lakes of Pré and Magnano (Fig. 4).

In the SE sector of the IMA more than half of the Magnano and of the Serra frontal moraines, built by the Viverone glacial lobe, were destroyed by the synchronous outwash activity. This is certified by the sharp truncation of these two morainic groups between the Cavaglià and Santhià villages (b in Fig. 4) and by the presence of a relict group of low moraines, outcropping 2.5 km downstream of the current boundary of the IMA in the middle of the glaciofluvial external plain, on which the Alice Castello village lies (c in Fig. 4). The isolated ridges of Alice Castello can be referred to the Magnano synthem owing to their distal position (Fig. 7). Further to the SW, in the subsoil of the external outwash plain between the Maglione and Alice Castello villages, a buried subglacial diamicton outcrops in a quarry documenting a previous, not be quantified, greater extension of the Vische glacial lobe downstream beyond the quarry site (Gariglio quarry; Carraro, 1992, 2012).

The Magnano moraines were initially referred to the Riss (Penck & Brückner, 1909; Sacco, 1927; Gabert, 1962). Carraro (1992) first recognized in the Serra d'Ivrea group two pedounits of deposits with different weathering degrees, but cartographically undifferentiated. Subsequently Gianotti (2007) distinguished an outermost Magnano alloformation from an innermost Serra alloformation still on pedostratigraphical basis: despite both units having soils with the same maximum hue index (7.5YR), they show a marked difference in the preservation of weathered deposits on the surface, which are much more widespread on the Magnano moraines, probably as a result of a greater soil thickness and evolution. A stark contrast in the weathering degree is evident in many places of the IMA at the border between the two units, as at the football field of the Orio village.

The moraine ridges reach their maximum altitude of 800 m a.s.l. at the proximal edge of the unit near Croce Serra (Andrate), and the minimum of 331 m a.s.l. with the crest of the Quinto moraine (Cavaglià). The depositional top of the succession is characterized by reddish-yellow soils with maximum hue color of 7.5YR and moderately weathered clasts.

The Magnano synthem is differentiated from the outermost Torrazzo synthem as they belong to different pedogroups based on index color (hue 7.5YR versus 5YR, respectively). Moreover the moraines morphology is characterized by remarkable continuity, much better than the Torrazzo moraines. The Magnano synthem can be separated from the innermost Serra synthem still on pedostratigraphical elements, but based on a higher weathering degree. The Magnano moraines are well formed and rather continuous, morphologically not very different from the Serra moraines, except for their lower elevation and the slightly higher degree of remodelling of the ridges.

5.13. Serra synthem

Most of the IMA, comprising the Serra d'Ivrea lateral moraines, are grouped into the Serra synthem. This unit roughly corresponds to an intermediate sector of the Serra d'Ivrea group (Carraro, 1992), from which the outermost Magnano synthem and the innermost Piverone subsynthem were separated (Gianotti et al., 2008). It includes the glacigenic deposits related to the eighth glaciation recognizable in the IMA. Currently it is considered as a pre-LGM unit referred to the penultimate glaciation (MIS 6).

The Serra synthem has been named after the Serra d'Ivrea, the biggest lateral moraine of the Dora Baltea basin. In detail, the Serra d'Ivrea is composed of seven to eight huge lateral moraines stretching 16 km along the internal side of the left sector of the IMA. In every stretch two to three parallel moraine ridges are present together, with only one being the main moraine. This elevated crest gradually lowers downhill and every 1-2 km distance it leaves the role of main ridge to the next outermost moraine.

The Serra d'Ivrea morainic complex was first referred to the last glaciation Würm by Penck (Penck et al., 1894; Penck & Brückner, 1909) (Fig. 3a) and in the first edition of the Ivrea Sheet of the Geological Map of Italy (Franchi et al., 1912). Successively, Gabert (1962) considered the Würmian as only the internal part of the Serra complex, and Rissian its external part. The whole Serra was instead referred to the penultimate glaciation (Riss) by Sacco (1927), in the second edition of the Biella Sheet of the Geological Map of Italy (Bortolami et al., 1966), by Carraro & Petrucci (1969) and Carraro et al. (1975) (Fig. 6C). Carraro (1992), abandoning the Penck & Brückner terminology, established a Serra d'Ivrea group of Middle Pleistocene age.

More recently the Serra group was referred to the Late Pleistocene by Arobba et al. (1997), according to the stratigraphy from the Alice Lake core (see 6.2). In contrast, Gianotti et al. (2008) correlate the Serra synthem to the penultimate glaciation (MIS 6, end of the Middle Pleistocene) on the basis of the same Alice core and according to the pre-LGM ^{10}Be exposure ages of erratic boulders from the outermost Serra moraine.

The boundary between the Serra synthem and the outermost Magnano synthem is the only one in the IMA stratigraphy based solely on a different weathering degree, which, however, does not reflect in the soil color (hue 7.5YR), while a buried stratigraphical marker has not yet been found.

The Serra synthem is differentiated from the innermost Ivrea synthem (MIS 2 glaciation) according to the facies analysis of the Alice Superiore core sequence, that fixed the Piverone subsynthem outer boundary (= LGM limit) as corresponding to the first moraine alignment located external to the drilling site (Fig. 7).

The Serra synthem can be subdivided on morphostratigraphical basis into two subsynthems, here named External Serra subsynthem and Internal Serra subsynthem, with the same boundary as that mapped by Gabert (1962). This corresponds to a morphological change from an outer unit (External Serra s.) with a partially discontinuous distribution (very similar to that of the Magnano synthem) to an inner unit (Internal Serra s.) characterized by a high degree of continuity (similar to that of the younger Piverone subsynthem) (Fig. 7).

Together with the preliminary data from the analysis of the Torre Canavese core, presently in progress (see 6.1), a series of arguments in favour of an LGM age of the Internal Serra unit are expressed in the discussions (see 8). However, in the absence of robust evidence, a more cautious reconstruction is proposed, i.e. External and Internal Serra subsynthems both of MIS 6 age, according to the previous state of knowledge about the amphitheatre stratigraphy.

5.13.1. External Serra subsynthem

The External Serra subsynthem (unit 16 in Fig. 7) contains the outermost high moraines of the Serra d'Ivrea complex. It has a wide but discontinuous extent, because it is repeatedly truncated by some of the big lobe moraine ridges (Viverone LS at Cavaglià, Borgomasino sub-LS at Villareggia and Strambinello LS at Baldissero) of the subsequent Internal Serra and Piverone subsynthems.

In the IMA eastern sector this unit has a distribution very similar to that of the Magnano synthem, made of two big straight lateral moraines, corresponding to the outermost ridges of the Serra d'Ivrea, which extends for 15 km between Castel Rubino (Andrate) and the Zimone village.

Some big erratics of eclogitic micaschist occur on the crest of the outermost of these moraines and two of them were sampled for cosmogenic ^{10}Be dating (Gianotti et al., 2008). According to the new production rates for ^{10}Be (recalculated based on Balco et al., 2009), the boulders have exposure ages of 30.8±3.5 ka (Ivrea7) and 35.0±3.9 ka (Ivrea8). The ages for these two boulders are minimum ages in light of the weathering of both the moraine itself and the boulder surfaces, suggesting a pre-LGM age for this moraine.

Downstream of Zimone these moraines become arched in plan view as they forms a series of lobe morainic ridges continuing for another 9 km between Zimone and Cavaglià, including the Zimone and the impressive Salussola small LS (7 in Fig. 4). Here the morainic alignments multiply becoming four (Zimone, Salussola, Dorzano) up to six (East of Cavaglià).

In the western sector the External Serra subsynthem forms the intermediate ridges of the Alice Superiore and the Strambinello LSs developed in the Chiusella Valley, joined by a 3 km long lateral moraine east of Lugnacco that forms the local watershed between Chiusella and Dora Baltea basins.

The unit has a particularly wide extent in the western sector between Torre Canavese and Mazzé, where it reaches its maximum width and surrounds wide intermorainic depressions (Vialfré peat bogs). From the culmination of these crests (Madonna della Rotonda NE of Agliè at 490 m a.s.l., S. Stefano near Candia at 431 m, and Monte Bicocca North of Mazzé at 344 m) are the popular panoramic views reported by Martins and Gastaldi (1850). In the Mazzé gorge, where the Dora Baltea flows out of the amphitheatre, the 80 m upper succession forming the Monte Bicocca moraine is made of subglacial melt-out till constituted of fine sands very poor in clasts, from massive to locally laminated (Fig. 10B), containing small blocks of fossil-bearing sandstone at the top. Based on lithofacies and paleontological content these sediments were assigned to a Pliocene glaciomarine environment by Bruno (1877). On the contrary, they are derived essentially from the subglacial resedimentation in submarginal position of Pliocene marine sands.

In the IMA southeastern frontal sector, the External Serra synthem is only partially preserved and forms the outermost moraines, owing to the gradational processes (glaciofluvial erosion and sedimentation) linked to the following expansions.

The top depositional surface reaches its maximum altitude of 860 m a.s.l. at the proximal edge of the unit near Croce Serra (Andrate) in the eastern sector and of 788 m a.s.l. with the Ripa Meugliano crest, in the western sector. This unit is characterized by reddish-yellow soils with maximum hue color of 7.5YR and moderately weathered clasts. A strong brown color 7.5YR 5/8 is measured in the truncated thin B horizon or in its derived colluvial products, while the transitional C horizon is several meters thick and shows a typical yellowish brown 10YR 5/6 in the middle sands lenses and an olive yellow 2.5Y 6/6 in the diamicton layers.

5.13.2. Internal Serra subsynthem

The Internal Serra subsynthem (unit 18 in Fig. 7) has a continuous extent along the whole amphitheatre, resulting in the most extensive unit of the IMA. In the eastern sector this unit corresponds to the innermost ridges of the Serra d'Ivrea morainic complex, extending for 16 km between Priat and Zimone and strongly parallel to the lateral moraines of the External Serra subsynthem. At Priat (NW of Andrate) the Serra d'Ivrea starts abruptly at 939 m a.s.l. (maximum IMA elevation) in correspondence to the outlet of Viona Valley. Here the moraine crest is suspended at a height of 680 m above the alluvial plain of the Dora Baltea River at San Germano (260 m a.s.l.).

In the first 3 km from Andrate the Internal Serra moraines form the more elevated ridges of the Serra d'Ivrea complex. Downstream of Zimone the unit widens greatly, rising from 1 km wide up to 2.5 km at Roppolo (the largest extent in the IMA for a single unit), where six arched moraine alignments occur to form the left sector of the big Viverone LS.

The Brosso-Strambinello lateral moraine complex in the western sector is the equivalent of the Serra d'Ivrea in the eastern sector. However, in this side the moraines show a much less regular trend because they spread to form the internal ridges of the Alice Superiore and the Strambinello LSs developed in the Chiusella Valley. The ridge begins at 831 m a.s.l. close to the Brosso village, therefore 100 m lower than the Serra onset in the opposite sector, because the Brosso moraine is 2.5 km further from the Dora Baltea Valley outlet than the corresponding Andrate moraine. South of the T. Chiusella incision the unit becomes very large and surrounds the widest intermorainic depressions of the IMA hosting the San Giovanni dei Boschi peat bog. In the frontal sector this unit branches into three main lobe complexes of Viverone, Settimo Rottaro and Vische (Fig. 4), each with its own lateral and frontal moraines ensemble. These glacial lobe systems were already set up during the previous glaciation, but part of the older moraines were later erased by subsequent glaciofluvial outwash processes, especially in the Villareggia-Cigliano area and at Cavaglià.

The top depositional surface locally preserves reddish-yellow soils with maximum hue color of 7.5YR and fairly weathered clasts, apparently not markedly different from those of the External Serra subsynthem (but see 5.15).

5.14. Rio Rudo palaeosol and other MIS5 markers

In contrast to the stratigraphic markers that separate the oldest glacigenic sequence, that all crop out in the outer northeastern sector of the IMA, the interglacial layers that split the more recent succession come from the inner western sector.

Here an exposed palaeosol (Gianotti, 2007) and an interstadial buried peat level (Alice Superiore unit) sampled through a core (Arobba et al., 1997) divide the Serra and Ivrea synthems.

A complex glacigenic succession is well exposed in the right side of the Rudo stream deep incision, close to the San Martino Canavese village. A red weathered layer referable to a B-C soil horizon transition is present at the summit of a subglacial glacigenic sequence and is covered by another body of subglacial till (Fig. 9A). Locally a decimetric layer of silty sands rich in vegetable macro rests lies on the palaeosol and is covered by the subglacial till. The out of range dating of a wood fragment (> 50 ka ^{14}C BP) indicates a pre-LGM age of this layer and of the lower glacigenic succession. The upper till may be correlated to the first outermost moraine that is referred to the Piverone subsynthem. Thus the Rio Rudo palaeosol is a stratigraphical marker separating the Ivrea synthem from an older underlying unit that can be tentatively referred to the Serra synthem.

The palustrine level at 52 m of depth in the Alice Superiore core (see 6.2 and 7) and older than 43 ka ^{14}C BP (Arobba et al., 1997) is more problematic to date. Comparing its pollen association with the data of Azzano Decimo core (Pini et al., 2009) the Alice Superiore unit can be attributed to MIS 7c or MIS 5c (Gianotti et al., 2008) (see 7).

5.15. Ivrea synthem (MIS 2)

The Ivrea synthem includes the glacigenic deposits of the last glaciation distributed in the entire Dora Baltea basin. They form the innermost morainic circles of the IMA, referred to LGM, and constitute also the numerous and widespread features of the recessional sequence distributed in the mountain basin, referred to the LGM (29-19 ka BP) and Lateglacial (19 ky-11.6 ka BP). The unit name was already used in the sheets of the Geologic Map of Italy (Dal Piaz et al., 2010; Carraro et al., 2012) to indicate the LGM to Lateglacial sequence in the Aosta Valley.

Geochronological datings are not available for the outermost moraines of the Ivrea synthem, but their age is constrained between the following dating: a maximum age is supplied by the ^{10}Be exposure ages on erratic blocks from the Serra d'Ivrea outermost ridge (see 5.13.1); minimum ages for the IMA deglaciation are supplied by ^{10}Be exposure ages in the Ivrea Hills sector as discussed below (see 5.15.4 and section 7).

On pedostratigraphic grounds the Ivrea synthem is considered to be the most recent unit of the 7.5YR pedogroup. The deposits are scarcely weathered at the top into <1 m thin soils, with yellowish-brown 10YR 6/8 color and little to no altered clasts. Also these soils are truncated, as proved by the diffusion of scattered thin bodies of soil-derived colluvial deposits with a yellow-reddish color (7.5YR 6/8, 5/6 and 5/3). A layer inversion in the colluvial products is typical, consisting in a yellow-reddish 7.5YR colluvium covered by a yellowish 10YR colluvium layer.

The presence of alignments of typical ice-marginal landforms (moraines and kame terraces) allowed recognition of five recessional stadials in the amphitheatre related to the LGM, and six recessional stadials in the Dora Baltea Valley related to the LGM and Lateglacial (Gianotti et al., 2008). According to the new data, the Ivrea synthem in the IMA is divisible, on morphostratigraphical basis, into the following seven subsynthems: Piverone (surrounding the Viverone and Candia lakes) corresponding to the LGM maximum expansion; Palazzo (which delimits upstream the same lakes), Andrate (forming the Piccola Serra-Strambino-Parella morainic circle) and finally the Pavone, Bienca, Prà San Pietro and Germano subsynthems (resting on the Ivrea Hills), corresponding to the main recessional stadials still of LGM age.

5.15.1. Piverone subsynthem (LGM glacial acme)

The Piverone subsynthem is the oldest unit forming the Ivrea synthem and includes the glacigenic deposits referable to the maximum expansion of the Dora Baltea Glacier during the climax of the last glaciation (LGM high glacial). This unit has a widespread and continuous distribution in the internal sector of the amphitheatre, quite similar to that of the outermost Serra synthem. Differently from the Serra synthem made of big moraines, it is represented by low and discontinuous moraines and mainly by numerous kame terraces composed by glaciolacustrine (Fig. 10C) and delta-fan marginal deposits. Numerous villages (from east to west: Piverone, Viverone, Azeglio, Settimo Rottaro, Borgomasino, Vische, Mercenasco, Scarmagno, San Martino and Strambinello) are located on the ridges of this large and low-relief unit.

This unit was attributed to the Würm or to the Riss glaciation by the different authors, together with the Internal Serra subsynthem from which the Piverone subsynthem was not differentiated.

A Piverone alloformation was first named and mapped by Gianotti et al. (2008) who distinguished it from the Serra d'Ivrea group, corresponding to the B unit of the Alice Superiore core of Arobba et al. (1987), but enlarging its external portion (see section 6.2 and Fig. 14). The Piverone alloformation was differentiated from the Bollengo-Albiano group (Würm/LGM unit, renamed here as Andrate Subsynthem) on pedostratigraphical basis, because of a very different thickness of the transitional C horizon of soils. The Piverone alloformation was so referred to the same Würm/Last Glacial Cycle of the Ivrea unit, but hypothetically linked to the MIS 4 stadial (Gianotti et al., 2008). The difference in the soil profile has now been recognized to be due to morphological (intermorainic valley outlets) and hydrogeological (ground water flow) local conditions and so it should not have a clear chrono-stratigraphic meaning. All of the Ivrea synthem sequence (starting from the Piverone subsynthem) can be so most likely referred to the MIS 2 stadial.

5.15.2. Palazzo subsynthem (LGM stadial)

Clearly different from the Piverone subsynthem in its distal sector, the Palazzo subsynthem is represented by a group of moraines forming an innermost discontinuous arc, on which the Palazzo, Strambino, Quagliuzzo and Loranzé Alto villages are located. These subsynthems worth being distinguished, as the Piverone moraines surround the lake basins of Viverone and Candia downstream, while the Palazzo moraines border the basins upstream.

In the distal sector the Palazzo subsynthem glacial deposits form the two relicts of a morainic arc, separated by the Dora alluvial plain, on which the Vestigné cemetery (left side) and the Strambino village (right side) lie. These low ridges acted as obstacles to the following glacial re-advance during the Andrate stadial. So the Dora Baltea Glacier constructed another set of terminal moraines against them and the Palazzo and Andrate subsynthem tills are closely welded.

5.15.3. Andrate subsynthem (LGM stadial)

The Andrate subsynthem consists of two lateral moraines (the Piccola Serra moraine on the left and the Parella moraine on the right; Figs. 10E-F) and a frontal moraine at Strambino. This discontinuous morainic arc is also named the “small morainic amphitheatre” by the locals. It corresponds to the Bollengo-Albiano group (Carraro, 1992), dated to the Late Pleistocene. Previously these deposits have been considered as the maximum expansion of the Würmian glaciation, from Sacco (1927) up to Carraro et al (1975). The LGM external boundary was later moved outwards 0.5-4 km in the lateral sectors and up to 13 km in the frontal sector, by considering the Piverone subsynthem as the outermost unit of the Last Glacial Cycle in the IMA (Gianotti et al., 2008).

The glacial deposits rest on an abrasion surface moulded on bedrock (at the valley mouth and on the Ivrea Hills, Figs. 3A-B), on the Pliocene marine substrate (at the internal depression bottom) and laterally against the same marine sediments (into the Chiusella incision, Figs. 3C-D) and the glacigenic deposits of the Palazzo subsynthem. The main morphologic element of this unit is the Piccola Serra, a 8.6 km long lateral moraine with a slightly curved shape in plan. It starts at the Andrate cemetery at 850 m a.s.l. and ends abruptly at the Bollengo castle at 316 m a.s.l. (Martins & Gastaldi, 1850; Baretti, 1877). The villages of Andrate and Burolo are located on its crest, while the Bollengo village lies at the foot of the moraine end. The continuation of the glacial deposits in the subsurface of the alluvial plain is unrevealed by the presence of a hydrogeological divide identified in the subsoil (Adorno, 1989).

In the frontal sector a well expressed frontal moraine is preserved, at 280 m a.s.l., on which the Romano and Perosa villages lie. It separates an external high outwash plain suspended at 260-248 m a.s.l. above an internal lower terraced outwash plain at 238 m a.s.l. with a peat bog (Cascine di Romano). In the western sector the morainic arc is represented by a less evident lateral moraine than the Piccola Serra, on which the Parella village lies, that dams the Alice Lake depression. Stratified fossil-bearing deposits with dropstones crop out in the southern internal slope of the Strambinello LS and correspond to the Pliocene glaciomarine deposits of Bruno (1877) (see 4). They form limbs laterally leaned upon a palaeo-scarp moulded into the marine substrate, now exposed by the Chiusella stream lateral erosion. They are so interpreted as marginal glaciolacustrine deposits of LGM age referred to the Palazzo and Andrate subsynthems, sedimented into marginal and ice-dammed lakes between the retreating glacier front and this scarp of marine deposits (Gianotti, 2007). The Pliocene fossil content (micro- and macrofauna and pollen) was supplied from the scarp to the lake environment by means of gravitative mass transport (debris fall and mud flow) passing to turbiditic currents. The very low transport rate, mostly into the lake, allowed good preservation of part of the fossils and the lack of reworking features.

5.15.4. Pavone subsynthem and other LGM stadials of the Ivrea Hills

The Pavone subsynthem is represented by a notable frontal moraine, 600 m long and 4-5m high, standing alone on the bedrock of the Ivrea Hills between Ivrea and Pavone (a in Fig. 11). Together with two other lateral moraines on the right side (above the Fiorano village, b in Fig. 11) and on the left side (on the M. Albagua SW of Chiaverano, c in Fig. 11), it forms a terminal morainic arc.

The other records of glacier retreat (after Pavone, the Bienca, Prà San Pietro and Germano allomembers in Gianotti et al., 2008) are represented by small and discontinuous moraines also exposed on the Ivrea Hills. In the internal plain, glacial deposits are buried below lacustrine and alluvial sediments. Consequently, the complete reconstruction of the ice margin is highly speculative here (Fig. 11).

Three erratic boulders from the Ivrea Hills were sampled for cosmogenic nuclide dating (Gianotti et al., 2008). We recalculated the ^{10}Be exposure ages based on recently determined production rates as described in section 7. Ivrea6 is a granite erratic block, resting just south of the Sirio Lake on the summit of the Monte Brogliero rocky hill at 317 m a.s.l. From it we obtained the oldest age (23.8±1.7 ka), that records deposition at the Dora Baltea Glacier margin, while its front was withdrawing from the Pavone Stadial to the subsequent Bienca Stadial position. Ivrea1 is a similar granite erratic block, whose position on the summit of the Ronchesse hill, east of the Pistono Lake, is just slightly more proximal than the Prà San Pietro Stadial position. The exposure age of this block is 20.1±3.0 ka, and may relate to a phase of glacial retreat between the Prà San Pietro Stadial and the Germano Stadial positions. The granite boulder Ivrea3 is located on a *roche moutonnée* above Nero Lake, not far from the Ivrea1 sample site and in a similar stratigraphic position. Nevertheless, it has a much younger exposure age (15.4±1.2 ka) likely related to surface erosion of the boulder.

On the basis of the form, extent, and distribution of glacial landforms and deposits, the following evolution is recognized (Gianotti et al., 2008). A wide area of granulite *roches moutonnées* without till cover is present in the distal sector of Ivrea Hills between Pavone and Chiaverano. This suggests a rapid downwasting of a clean Dora Baltea glacier (very little surface or entrained debris) after the Andrate and the following Quintas Stadial. Only to the SW of Ivrea does the Pavone morainic arc indicate a brief glacier readvance. During the Bienca Stadial, a glacial lobe persisted on the left side of the glacier in a large depression of the northern sector of Ivrea Hills, where some concentric moraines and kames are present (Forno et al., 2005b). An ice-damned lake formed in the Bienca hollow as the glacier retreated (Prà San Pietro stadial). Similar sequences of moraines, kame terraces and lower lacustrine terraces recur in various depressions between the hills at different elevations, with the last one in the more proximal Lago Nero hollow (Germano stadial) (Forno et al., 2007). By the Germano stadial, the Dora Baltea Glacier had definitively left the IMA.

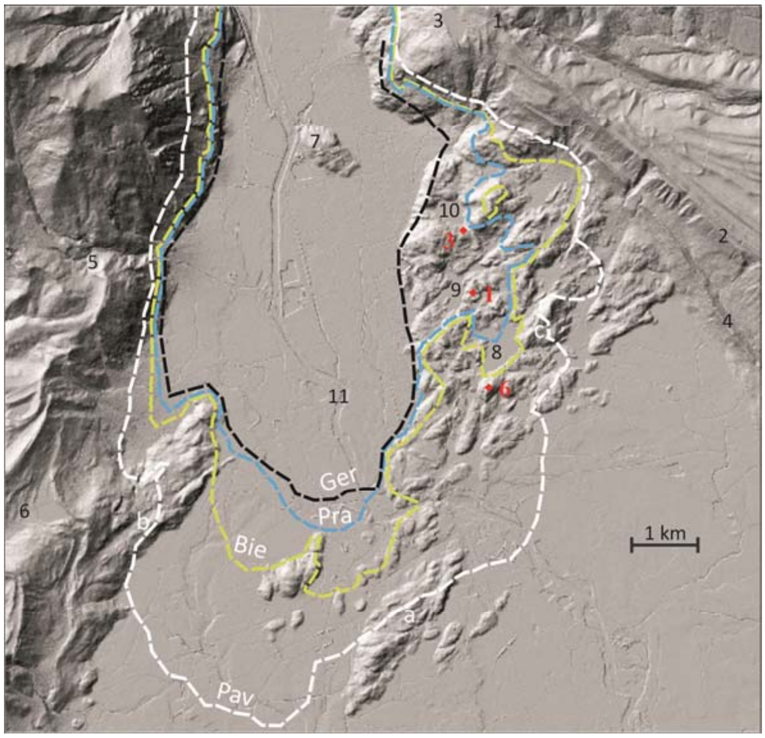


Fig. 11 - Reconstruction of the halts of the Dora Baltea Glacier front during the LGM stadials in the Ivrea Hills area: Pavone (Pav), Bienca (Bie), Prà San Pietro (Pra) and Germano (Ger) stadials. Locations of samples (Ivrea1, 3 and 6) for ^{10}Be exposure dating are indicated by red numbers and symbols. 1) Starting point of the Serra d'Ivrea; 2) Serra d'Ivrea moraine; 3) starting point of the Piccola Serra at Andrate 4) Piccola Serra moraine; 5) starting point of the right lateral moraine at Brosso; 6) Alice Superiore LS and Lake; 7) Monte Buono monadnock; 8) Sirio Lake; 9) Pistono Lake; 10) Black Lake; 11) Dora Baltea River (on DTM, courtesy of Piedmont Region).

5.15.5. Lateglacial and Holocene

During the Alpine Lateglacial (19-11.6 ka BP) the Dora Baltea Glacier was completely retired upstream of the IMA, according to the ^{10}Be exposure ages from the Ivrea Hills erratics. The elements that allow recognition of the successive six halts (subsynthems corresponding to glacial stadials) of the glacier during the recessional phase into the Dora Baltea Valley are (Fig. 1; Gianotti et al., 2008): a frontal moraine in Torredaniele, 82 km from Monte Bianco (Torredaniele Stadial); a concentration of granitic erratic blocks in the valley floor near Bard (Bard Stadial; Carraro, 1992); alignments of kame terraces, 18 km long on the left side of the valley between Roisan and Chambave, connected with lateral-frontal relics of moraines 58 km from Monte Bianco (Chambave Stadial, only in part equivalent to the Chambave stadial of Novarese, 1915); a frontal arc dissected by the Dora Baltea River near Saint Pierre, 26 km from Monte Bianco (Saint Pierre Stadial); a group of lateral moraines on the right of the valley floor at La Villette and Dolonne near Courmayeur, at only 3 km from actual Brenva Glacier front (Courmayeur Stadial; Porter & Orombelli, 1982; Carraro et al., 2012), and a terminal moraine in the Ferret Valley (Planpincieux Stadial; Porter & Orombelli, 1982). Two exposure ages were obtained from the distinctive *roche moutonnée* of the lower Dora Baltea valley floor, near Donnas village (Gianotti et al., 2008). The ages 16.9±1.4 ka (Ivrea10) and 16.2±1.0 ka (Ivrea11) provide a minimum age for the retreat of the glacier between the Torredaniele Stadial and the Bard Stadial positions.

Also the sedimentary infilling history of the IMA internal depression that began during the LGM stadials is as well poorly constrained. Recently, geophysical surveys in and around the Candia Lake, located in the internal depression of the Candia LS, were carried out (Colombero et al., 2014). They consisted of an extensive waterborne continuous vertical electrical sounding (CVES) and self potential (SP) data recorded on the lake surface, and three electrical resistivity tomographies (ERTs) on land near the lake shores. The geophysical data suggest that the proximal (northern) sector of a proglacial lake wider than the present Candia Lake was filled by an advancing fan-delta, directly fed from the glacier meltwaters, during the Palazzo stadial (Fig. 12). The basin was not completely filled because the fast glacigenic sedimentation stopped suddenly due to a more pronounced glacial retreat. The glacier withdrew up to the front halt identified by the Andrate subsynthem end moraines 5 km upstream. A much slower lacustrine sedimentation continued into the relict basin. A similar evolution can be proposed for the largest Viverone Lake, which occupies the internal depression of the Viverone LS.

Only a few lacustrine basins survived to the glacigenic filling processes in the internal plain; here a lacustrine and palustrine sedimentation could continue during the Lateglacial and Holocene, as recognized by palynological studies. Schneider (1978) first carried out palynologic analysis supported by radiocarbon dating in the IMA. Lateglacial and postglacial successions were analyzed in 9 cores from 7 sites of the western Alpine piedmont area (Trana in the Rivoli-Avigliana amphitheatre; *Torfsee* in the Ivrea Hills and Viverone and Alice Superiore mires in the IMA; Biandronno Lake in the Verbano amphitheatre). At *Torfsee* at 250 m a.s.l., a 10 ha wide marsh at NE of the Sirio Lake on the Ivrea Hills, a 5 m long core was drilled into a lacustrine and palustrine succession spanning from the Oldest Dryas to the Boreal. In the Logge mire close to the southern shore of Viverone Lake a 13 m deep drilling crossed mostly Holocene sediments (0-11.2 m) up to coarse deposits related to the Oldest Dryas, according to palynologic assemblages.

In the Alice Superiore mire (570 m a.s.l.) three 5 m long cores were collected, all of them reaching the Oldest Dryas layers. Wood and Cyperaceae from one core (profil 4) yielded the following uncalibrated radiocarbon ages: 11.72±0.24 ^{14}C ka BP, 11.49±0.15 ^{14}C ka BP, 9.85±0.12 ^{14}C ka BP, 5.14±0.1 ^{14}C ka BP. Another core (profile 5) provided the oldest radiocarbon age for the IMA (14.2±1.5 ^{14}C ka BP) obtained on clayey gyttja at 380-390 cm depth. This age, now calibrated to 17,704-16,806 cal BP, was so considered the minimal age for the IMA deglaciation, before the availability of oldest ages from the cosmogenic nuclide dating (Gianotti et al., 2008). In the uppermost sequence other ages (11.66±0.9 ka BP and 12.39±0.16 ka BP) were obtained.

In the Alice cores the lower palynologic unit is assigned by Schneider (1978) to the Oldest Dryas and it is referred to a tundra environment with herbaceous species (*Artemisia*, *Rumex* and Chenopodiaceae). During the Bølling interstadial, shrublands with *Betula* and herbs appeared, later developing into a denser pine woodland. The Younger Dryas experienced the reduction of forest cover and expansion of xerophytes (*Artemisia* and Chenopodiaceae). Compared with the palynologic spectra from the Northern Alps and middle Europe, the Alice spectra has a high rate of juniper just in the Oldest Dryas, indicating a favourable climate during all the Lateglacial, abundance of Larix in the second half of the Bølling and low values in the Oldest Dryas; the mixed oak spread during the Allerød, and rapidly decreased in the Younger Dryas.

On the Ivrea Hills, Forno et al. (2007) presented stratigraphical data from a succession cored in the northern sector of the Ivrea Hills. The Tomalino mire (381 m asl, Chiaverano) was manually cored in order to describe the sedimentary succession therein deposited and sample it for palynological investigations. Lacustrine - palustrine sediments cored at this site testify to deposition taking place in a basin no longer fed by a glaciofluvial stream, but instead controlled by the local morphology. As suggested by the comparison with the pollen record of Lago Sirio (Schneider, 1978), the oldest sediments retrieved can be as old as the second part of the Lateglacial interstadial or the Younger Dryas. Geomor-

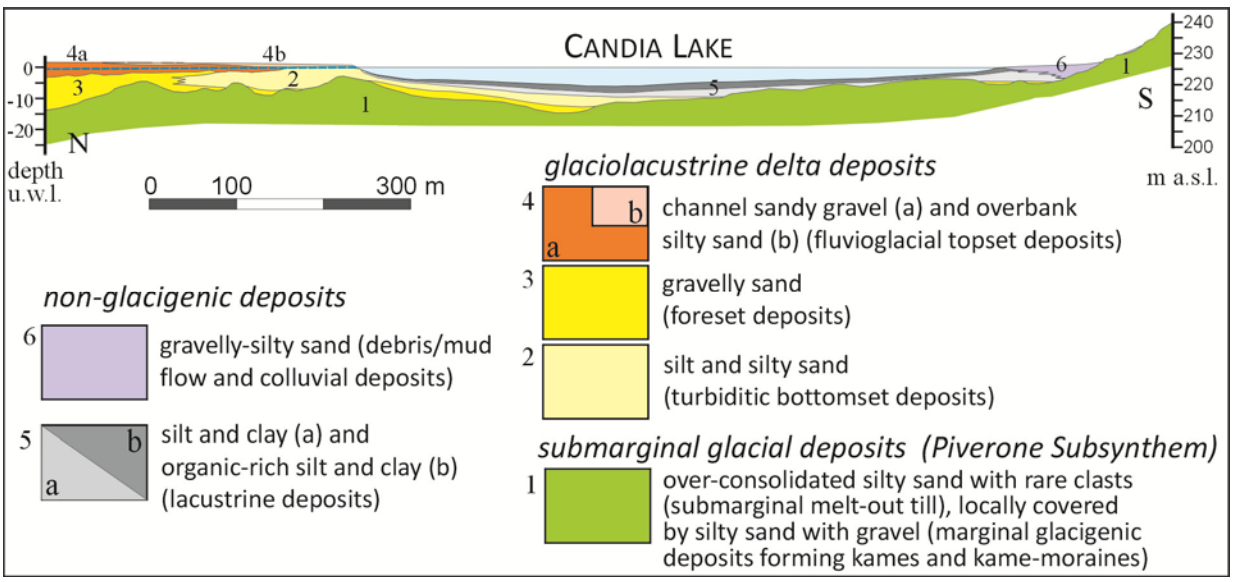


Fig. 12 - Geological cross-section of the Candia Lake area derived from geophysical surveys (from Colombero et al., 2014, modified). The articulated shape of the deepest resistivity boundary suggests the presence of buried kame-moraines of submarginal till (1). The extent of fine glaciolacustrine deposits (2 and 3) both under the lake and the plain suggests the wider extent of a former lake. The current Candia Lake is the relict of a wider ice-dammed lake, not completely filled up by deltaic deposits coming from the retreating Dora Baltea glacier. The filling up of the lake suddenly slowed down owing to the complete retreat of the glacier (5a) and continued so far (5b) by a moderate colluvial and alluvial supply from the southern side of the basin (6).

phological observations indicate that sedimentation started locally at least at the beginning of the Lateglacial.

6. DRILLING CORES IN THE PEDOGROUP C SUCCESSION

In the western sector of the IMA the most ancient units seem very reduced, not preserved or not recognizable. In contrast, the most recent units (7.5YR pedogroup C) reach in this sector their maximum size. Here, long lithostratigraphical logs from two continuous drill cores are available. The 82 m deep Alice Superiore core was drilled in 1984 for water research, analyzed by Arobba et al. (1997) and Gianotti et al. (2008) and re-interpreted in the present paper. The 55 m deep Torre Canavese core was drilled for stratigraphical purpose in 2013 by the writers, within the PROGEO Piemonte Project (Giardino et al., 2011), with the aim of investigating a possibly complete Late Pleistocene succession and to obtain elements for the dating of the Serra synthem.

A comparison between the Torre Canavese core (see 6.1) and the Alice Superiore core (see 6.2) highlights the similarity between the two sedimentary sequences, since in both cores two thick bodies of subglacial till are separated by a layer of interglacial/interstadial organic-terrigenous aquatic sediments (lacustrine at Torre, palustrine at Alice). It should however be taken into account that the two cores have different locations, because the Torre core was collected from the middle of the Serra synthem moraines, while the Alice core was drilled on the Palazzo subsynthem kame terraces in a more internal position (Fig. 4).

6.1. The Torre Canavese core

A 55 m long core was drilled in 2013 into the sedimentary sequence of the Serra unit South of Cascina Zucca between the Torre Canavese and Silva villages (2 in Fig. 4). The core was drilled into a small depression in the western lateral sector of the IMA, where the Serra unit reaches its maximum width. Moreover, the elevation (410 m a.s.l.) and the isolated location of the site in the middle of the Serra moraines prevented any glacigenic deposit supply during the subsequent Piverone expansion, in order to ensure the persistence of a lake characterized by slow and continuous sedimentation. Only part of the preliminary results of this work are outlined below and discussed in section 8.

The drill crossed the entire local glacigenic succession until the pre-glacial substrate at 53 m depth. This substrate corresponds to Lower Pleistocene fluvial deposits, made of weathered clast-supported sandy gravels derived from the Chiusella Valley, a local catchment basin confined to the Sesia-Lanzo Zone. Two about 10 m thick lacustrine sequences were cored, each resting on a subglacial till body with a thickness of 12 and 20 m, respectively. The upper till body is been obviously attributed to the Serra synthem (Fig. 13). The top of the upper lacustrine sequence is Holocenic according to two radiometric datings (2343±27 ^{14}C a BP at 2.60 m depth corresponding to 2460 to 2320 cal BP; 8466±35 ^{14}C cal a BP at 3.37 m depth corresponding to 9535 to 9440 cal BP). The top of the lower lacustrine succession has supplied an out-of-range date (> 45 ^{14}C ka BP at 29.30 m depth). A preliminary pollen analysis was carried out on 12 selected samples and a complete magnetic susceptibility and LOI analysis was performed (CNR-IDPA). Pollen spectra so far available do not support the chronological frame provided by ^{14}C ages. Pollen stratigraphy, although based on a limited number of samples, seems to suggest a Lateglacial age for the part of the sequence where ^{14}C dating yielded Holocene ages. Further analyses are in progress, both concerning pollen stratigraphy and radiocarbon dating, to fix this problem.

6.2. The Alice Superiore core

In 1984 a borehole for water research was drilled at 585 m in the internal depression of the Alice Superiore LS near the Alice Lake (1 in Fig. 4). The coring crossed a very varied and complex sedimentary succession up to 82 m of depth but without reaching the bedrock. At a depth of 52 m, a 1-m-thick peat layer was encountered between two glacigenic sequences (Fig. 14). Each sequence consists of glaciofluvial and glaciolacustrine deposits and flow till and includes a diamicton body with a thickness of 12 and 13 m respectively, interpreted as lodgement till. Detailed biostratigraphic data from the peat layer are presented in the following section 7. The peat layer has a radiocarbon age > 44.3 ka ^{14}C BP and referred as post-Eemian in agreement with *Fagus* pollen content. It was so considered as a Late Pleistocene interstadial marker referable to the MIS 5c, separating the Serra group deposits from the Bollengo-Albiano group ones. The entire Serra group was referred to the Late Pleistocene (Arobba et al., 1997). A different stratigraphical and chronological reconstruction was later proposed using the same data (Gianotti, 2007; Gianotti et al., 2008). On the basis of a MIS 5c age of the interstadial peat layer, two units were differentiated, the Serra alloformation of Middle Pleistocene age and the

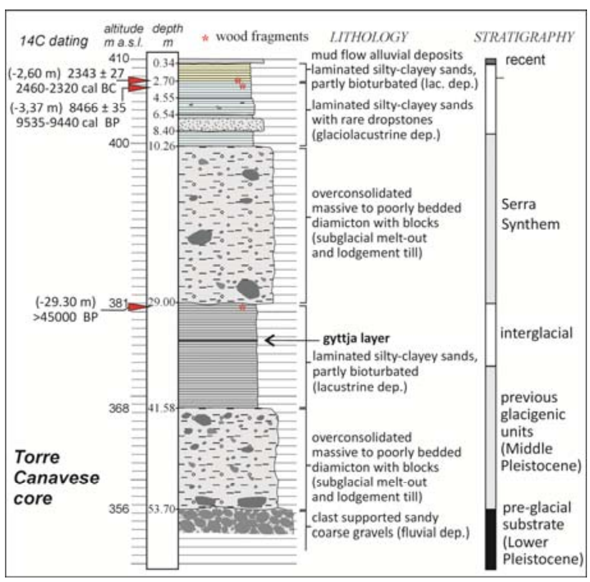


Fig. 13 - Lithological data and preliminary stratigraphical interpretation of the Torre Canavese log in the Ivrea morainic end system (2 in Fig. 5). Radiocarbon ages were calibrated using OxCal v3.10. Calibrated dates are with 95.4% probability.

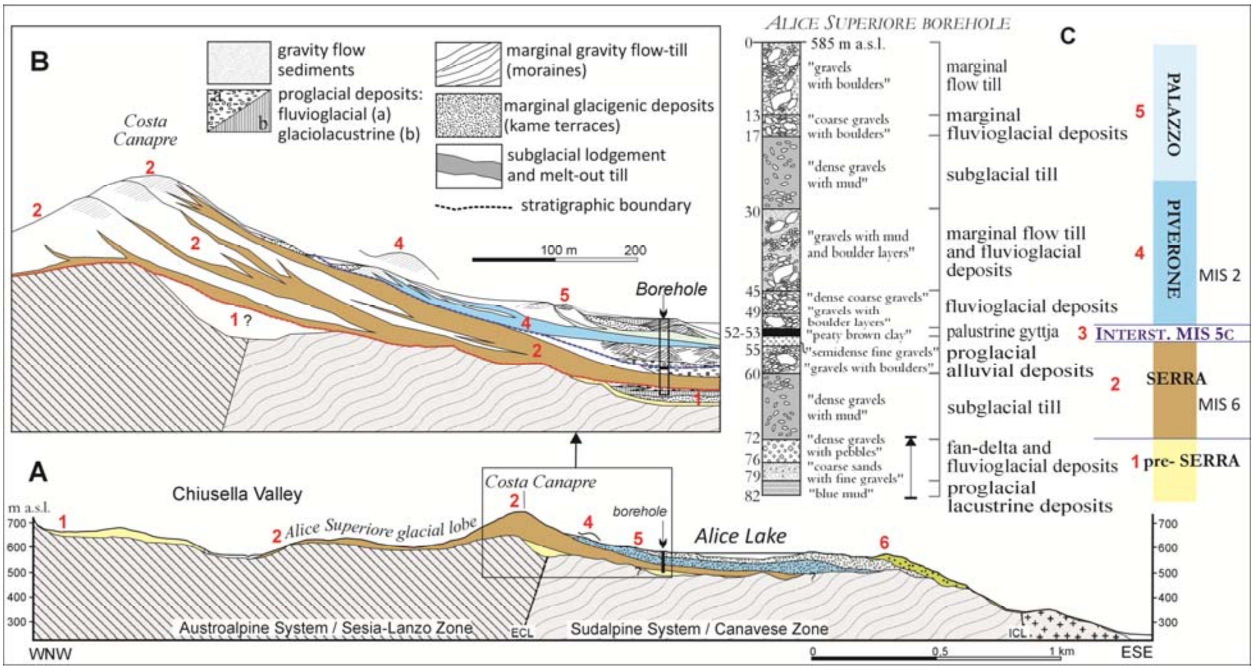


Fig. 14 - Stratigraphical reconstruction of the IMA northwestern sector (cross section trace b in Fig. 14), based on the attribution of the Alice peat layer to the MIS 5c interstadial (from Gianotti et al., 2008, mod.). According to this, the Serra Synthem (MIS 6) must correspond to the lower 12 m thick subglacial till body. The upper 13 m thick subglacial till body has to include the the Piverone and Palazzo subsinthems (MIS 2) and is correlatable with the slightly more external succession of moraines and kame terraces. The coarse gravels lying above the interstadial layer are referred to as anaglacial proglacial (45-49 m) and marginal deposits (30-45 m) of the Piverone Subsynthem. The similar coarse gravels lying at the top of the succession should be cataglacial proglacial (13-17 m) and stadial marginal deposits (0-13 m) of the Palazzo Subsynthem. In the detailed profile (B) only the subglacial tills are colored. The dotted lines indicate the basal surfaces of the LGM (blue line) and of the MIS 6 (red line) glacigenic successions.

Piverone alloformation of Late Pleistocene age. Without considering the new insights from the Torre Canavese log, two stratigraphical reconstructions are proposed for the IMA north-western sector assuming the two different chronological attributions of the Alice Superiore peat layer, correlated with the MIS 5c interstadial (Fig. 14) or to the MIS 7c interstadial. Based on facies analysis, each subglacial layer in the Alice core is correlated to moraines located in more distal positions. These marginal forms are part of the Alice Superiore LS, forming a huge morainic arc that extended up to the local edge of amphitheatre into the Chiusella Valley 3 km WSW from the coring site. Its main right lateral moraine (Costa Canapre moraine, reaching an elevation of 750 m) corresponds, on morphological grounds, to the Serra d'Ivrea moraine on the opposite side of the amphitheatre.

7. CHRONOLOGICAL CONSTRAINT

The chronology of AMI is supported by a few, but significant, dates, obtained by palaeomagnetic, radiocarbon and cosmogenic nuclide dating methods. Moreover, a series of chronologic constraints based on correlation of, still inadequate, biostratigraphic data are proposed.

The beginning of the IMA was referred (Carraro et al., 1991) to the Early Pleistocene-Middle Pleistocene boundary on palaeomagnetic basis, according to both reverse and normal magnetization of two glaciolacustrine sequences resting below and above subglacial till at Mongrando (see 5.1). Actually, according to the MIS chronology (Lisiecki & Raymo, 2005) this chronostratigraphic boundary falls within an interglacial (MIS 19), so the oldest glacigenic unit of the IMA (Mongrando synthem) likely holds the products of two different glacial expansions. This implies that only an ancient part (more external or underlying) of this synthem should be referred to a glaciation that occurred at the end of the Early Pleistocene, probably correlable to the MIS 20 or to the MIS 22, and the question requires further investigation. In this perspective, the closest reference stratigraphy is provided by the Bagaggera log core from the Southalpine plain NE of Milan (Scardia et al., 2010).

In the middle of the IMA eastern sector the stratigraphy of the pedogroups B (hue 5YR) is chronologically constrained by the marker layer of Cascina Gianetto (see 5.9). This gyttja layer is embedded between the glacigenic sequences of the Parogno and Torrazzo synthems. A preliminary pollen analysis was carried out on four selected samples from the Cascina Gianetto outcrop, to test the presence and the degree of palynomorphs preservation in different litologies (Gianotti & Pini, 2011). Pollen is abundant and well preserved. Pollen spectra are dominated by *Abies*, accompanied in the lowermost samples by *Corylus*, deciduous *Quercus* and *Ulmus* (Fig. 15). These compositions reflect the occurrence of dense fir-dominated forest at the regional scale under warm-temperate climatic conditions. A record of environmental and climate changes for the Middle-Late

Pleistocene of Northern Italy has been obtained on the Azzano Decimo core, a 255 m-long succession of marine-transitional-continental deposits retrieved in the Friulian plain (NW Italy). A palynological record is available for the whole sequence, but at the moment only data from the uppermost 95 m (ca. 20 - 215 ka BP) have been published (Pini et al., 2009). The pollen spectra from the Gianetto site can be compared with the Azzano Decimo core record. Due to the limited amount of data available from the Gianetto section, biostratigraphic correlation is at the moment tentative, but some hypothesis can be proposed. Among the Late and Middle Pleistocene *Abies*-dominated forest phases recorded in the Azzano Decimo core, two of them show major similarities with the Gianetto data, as for the lack or extreme scarcity of *Fagus* and *Carpinus betulus* pollen grains and the occurrence of *Corylus* and other thermophilous species. They are correlatable with the MIS 11.3 and the MIS 9.3 interglacial phases. A correlation of the Gianetto layer with the MIS 11.3 interglacial would fit well with the stratigraphical reconstruction proposed by Gianotti (2007) and Gianotti et al. (2008), as it is followed by four glacigenic units related to distinct glaciations (i.e. MIS 10, MIS 8, MIS 6 and MIS 2) (see Fig. 17). A more detailed palaeobotanical analysis of this layer could allow a better evaluation of its palaeoclimatic meaning and provide further support to the IMA climatostratigraphic subdivision.

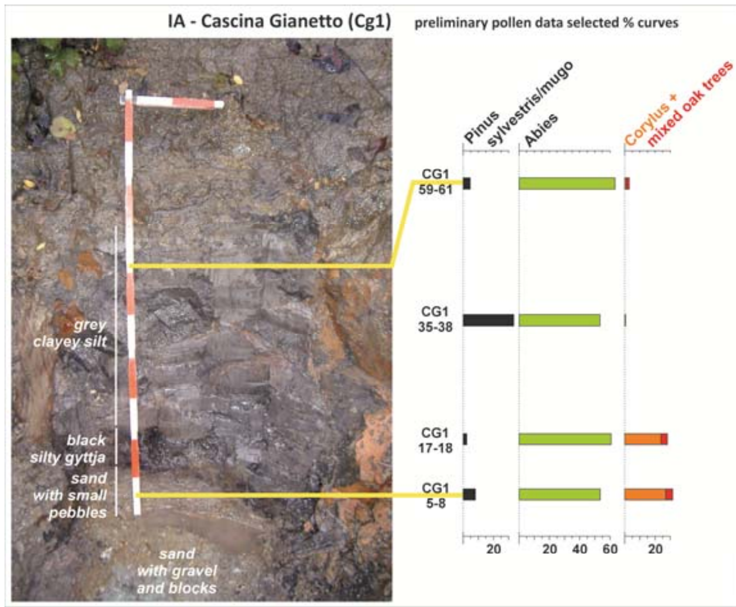


Fig. 15 - The lacustrine layer of Cascina Gianetto and its preliminary pollen data selected % curves (from Gianotti & Pini, 2011).

Concerning the chronological setting of the innermost IMA units, radiocarbon and ^{10}Be exposure ages and pollen spectra are available.

A precise chronological attribution of the interstadial/interglacial marker of the Alice Superiore core (6.2) is clearly the basis for the correlation of the IMA youngest units (External and Internal Serra, Piverone, Andrate) to the MIS stratigraphy. The Alice palynological spectrum (Fig. 16) was derived from a unique sample from the peaty clay layer at 52 m depth, with good preservation and high pollen concentrations (>111 000 grains/g). It indicates a moist and temperate forested environment (A.P. index 88,5%), characterized by the dominance of *Quercus* (25%), *Alnus* (17%), *Fagus* (13%) and *Betula* (6.2%) with smaller amounts of *Picea* (2.9%), *Carpinus* (2.5%), *Abies* (4.5%), *Tilia t. cordata* (1.7%), *Ulmus* (0.57%), Cupressaceae (0.57%) and *Salix* (0.29%). Herbaceous taxa (11.5%) are represented by Poaceae (1.41%), *Artemisia* (1.70%), Ranuncolaceae (1.41%), *Filicales monolete* (1.13%), *Sagittaria* (0.85%), *Potamogeton* (1.41%) and others (Arobba et al., 1997). Two possibilities are most probable for the age of the Alice Superiore layer, from comparison of the Alice palynological association and the Azzano Decimo stratigraphy (Pini et al., 2009): a MIS 7c age or a MIS 5c age (Gianotti et al., 2008). During MIS 7a-b-c, the Azzano profile shows long phases with *Fagus*-*Abies* dominance. The Alice spectrum is particularly similar to Azzano in MIS 7c, with *Fagus*-*Abies*-*Quercus* associations. Regarding the possible attribution to the MIS 5c, the first part of the Eemian in Azzano is characterized by the absence of both *Fagus* and *Abies*. The second part of Eemian shows *Abies* and *Carpinus* with subordinate *Fagus*. During MIS 5c, a short phase is similar to the Alice spectrum, unless the presence of *Betula* in the Alice sediments is due to the different environment and altitude (Azzano is near the Adriatic Sea at 20 m a.s.l., Alice is close to the Western alpine piedmont at 585 m). After MIS 5a, *Quercus* no longer dominates and forest associations as dense as those found at Alice are missing after the Dürnten phase (60 ka BP).

In the Dora Baltea basin 13 rocky samples were collected from erratic blocks and *roches moutonnées* (nine samples in the Ivrea Amphitheatre and four sam-

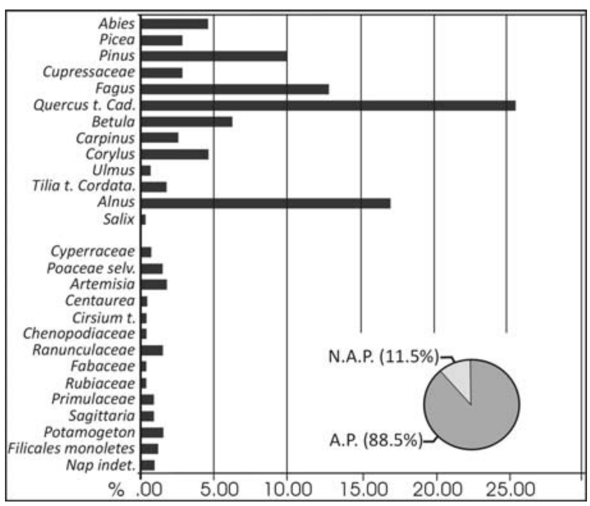


Fig. 16 -The Alice Superiore core palynological spectrum, derived from a unique sample from a peaty clayey layer at 52 m depth, with good preservation and high pollen concentrations (>111 000 grains/g) (redrawn from Arobba et al., 1997).

ples in the Aosta Valley) and dated using cosmogenic ^{10}Be (Gianotti, 2007; Gianotti et al., 2008). Here, we recalculate the ^{10}Be surface exposure ages reported in Gianotti et al. (2008) using the northeast North America production rate (spallation production rate of 3.88±0.19 ^{10}Be atoms g^{-1} yr^{-1}) and the time-dependent scaling model of Lal/Stone (CRONUS-Earth online calculator; Balco et al., 2008, 2009). Recent work at the Chironico landslide in the Leventina valley, Switzerland, where both exposure ages and radiocarbon dates are available, has shown that the northeastern North America production rate is well applicable at Alpine sites (Claude et al., 2014). For ease of further afield site comparison of ^{10}Be ages, we use the northeastern North America production rate rather than an Alpine specific local production rate. Work by several authors shows excellent consistency for ^{10}Be production rates from several widely spaced sites (summarized in Heyman, 2014).

Three basic chronological constraints have been provided by this dating method. The ^{10}Be exposure ages from the erratic boulders Ivrea7 (30.8±3.5 ka) and Ivrea8 (35.0±3.9 ka) suggest a pre-LGM age for the External Serra subsynthem (see 5.13.1). The ^{10}Be exposure ages from the various boulders on the Ivrea Hills indicate an LGM age for the innermost units belonging to the Ivrea synthem (see 5.15.5). In particular, the ^{10}Be exposure age from boulder Ivrea6 (23.8±1.7 ka) supplies the oldest age for last glacial deglaciation in the IMA. This age is in excellent agreement with the exposure ages from erratics from the outermost LGM moraines at Wangen (Solothurn, Switzerland) on the northern Swiss Alpine foreland. The data from Wangen indicate that the initial moraine abandonment was underway by 22.6±2.1 ka based on ^{10}Be ages for four boulders (Ivy-Ochs et al., 2006, recalculated according to the new production rates for ^{10}Be). Good correlation can be found also with the Remanzacco subsynthem recessional moraines in the Tagliamento Amphiteatre in eastern Italian Alps, dated between 22 and 18.5 cal ka ^{14}C (Fontana et al., 2014).

Before the nuclide cosmogenic dating, the minimum ages for the IMA deglaciation were supplied by uncalibrated radiocarbon dating on Lateglacial peaty sediments in the Alice Superiore Lake (14,200 ±150 ^{14}C a BP; Schneider, 1978) and in Villa Lake, in the lower Aosta Valley (12,700±130 ^{14}C a BP; Brugiapaglia, 2001). The first dating, now calibrated to 17,704-16,806 cal BP, is the oldest definite radiocarbon age obtained in the IMA (see 5.15.5 for the climato-stratigraphical framework reconstruction).

8. PROPOSED CRONOSTRATIGRAPHIC AND CLIMATO-STRATIGRAPHIC FRAMEWORK

The current updated knowledge on the IMA stratigraphy is based on the recognition of nine synthems ranging from the end of the Early Pleistocene to the Late Pleistocene.

At present, a cautious approach would refer the oldest glacigenic successions to the end of the Lower Pleistocene (Mongrando and possibly Bornasco synthems) and to the Middle Pleistocene glaciations (from Bornasco to Magnano synthems), without a precise correlation with the MIS stadials. The Serra synthem can instead be referred to the last glaciation of Middle Pleistocene age (MIS 6). The last Ivrea synthem is certainly referred to the LGM at the end of Upper Pleistocene (MIS 2).

The nine synthems can be only tentatively correlated to the glacial stadial of the MIS stratigraphy on the basis of their stratigraphical order and with the constraint of four main points: 1) the Early Pleistocene age of the first unit (Mongrando synthem), demonstrated by the reverse magnetization of its buried glaciolacustrine sediments; 2) the Cascina Gianetto layer possibly correlated to MIS 11c interstadial and separating Parogno from Torrazzo synthems (Gianotti & Pini, 2013); 3) the presence of three younger synthems (Magnano, Serra and Ivrea) consequently referred to the last three glaciations (MIS 8, MIS 6 and MIS 2); the LGM age of the innermost unit

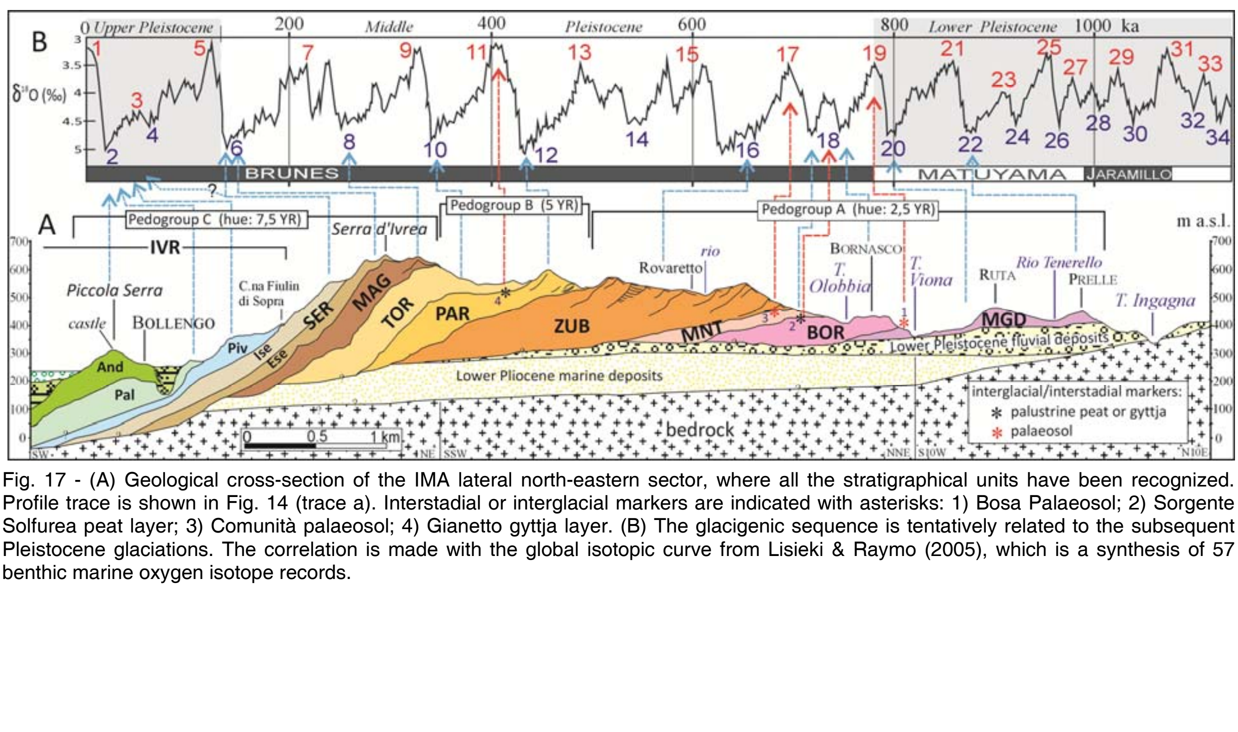


Fig. 17 - (A) Geological cross-section of the IMA lateral north-eastern sector, where all the stratigraphical units have been recognized. Profile trace is shown in Fig. 14 (trace a). Interstadial or interglacial markers are indicated with asterisks: 1) Bosa Palaeosol; 2) Sorgente Solfurea peat layer; 3) Comunità palaeosol; 4) Gianetto gyttja layer. (B) The glacigenic sequence is tentatively related to the subsequent Pleistocene glaciations. The correlation is made with the global isotopic curve from Lisieki & Raymo (2005), which is a synthesis of 57 benthic marine oxygen isotope records.

(Ivrea synthem) on the basis of radiocarbon and ^{10}Be exposure ages (Gianotti et al., 2008).

The stratigraphical reconstruction was based on the presence of interglacial/interstadial marker layers between the glacigenic sequences and on the distinction in pedogroups.

Concerning their range as a discontinuity, we consider that a palustrine layer made of gyttja or peat can be assigned to an interglacial or interstadial phase on the basis of its pollen content. Thus it delimits two synthems that, in absence of a detailed palynological study, can be referred to different 100 ka glacial cycles (i.e. MIS 10 and MIS 12) or to different expansion within the same glacial cycle (i.e. MIS 4 and MIS 2 of the Last Glacial Cycle). On the contrary, we consider an evolved palaeosol to have passed through at least one interglacial phase, thus it has to separate synthems of different 100 ka glacial cycles.

On the basis of these assumption and on the chronological constraints, a tentative reconstruction can be proposed to better fit the glacigenic units extent to the different peaks of the MIS stratigraphy (Fig. 17). First of all, the intermediate pedogroup B comprises the Parogno Synthem, correlated to the MIS 12, and the Torrazzo Synthem to the MIS 10, as they are separated by the Cascina Gianetto layer related to the MIS 11c interstadial. A weak global isotopic signal characterizes the MIS 14 yield to a lack of glacigenic products in the Alpine piedmont. On the contrary the MIS 16 strong climatic signal (Lisiecki & Raymo, 2005) seems the best fit for the wide extent of the Zubiena morainic complex. Moreover the MIS 18 shows two distinct peaks separated by a marked interstadial (Lisiecki & Raymo, 2005). These assumptions can be referred to the Bornasco and the Montino units as two distinct glacial advances correlated to the two peaks of the MIS 18 and separated by the Sorgente Solfurea peat layer related to the interstadial in between. In this case Bornasco (or the upper part of this unit) and Montino would became two synthems of the same 100 ka glacial cycle, each correlable to MIS 18. The oldest Mongrando synthem comprises glacial deposits that are correlated to the glacial stages MIS 22 or MIS 20.

The three glacigenic units (Magnano, Serra and Ivrea synthems) forming the more recent 7.5YR pedogroup C can be correlated to MIS 8, MIS 6 and MIS 2 glacial respectively. In detail, the recalculated ^{10}Be ages for boulders Ivrea7 and Ivrea8 from the outermost Serra of Ivrea crest support an MIS 6 age for this unit, according to the sharp cold signal for this stadial in the isotopic curve (Lisiecki & Raymo, 2005).

More detailed data are known about the last glaciation. The Ivrea synthem age is best constrained to MIS 2 by the somewhat older ^{10}Be ages from the Serra d'Ivrea boulders (Gianotti et al., 2008), the pre-LGM age of the underlying peat layer from the Alice Superiore core (Arobba et al., 1987), the LGM ^{10}Be exposure ages from the Ivrea Hills boulders (Gianotti et al., 2008) and the early Lateglacial radiocarbon ages from the Alice Superiore peaty bog (Schneider, 1978). The outermost unit of the Ivrea synthem, the Piverone subsynthem, is to be considered the maximum expansion stadial of the LGM, followed by the sequence of LGM recessional stadials corresponding to the Palazzo, Andrate, and Pavone subsynthems (and other less important units). The Piverone subsynthem and the regrouped Palazzo-Andrate subsynthems could form a complex similar to the Maximalständ and Hochständ of LGM end moraines observed in the Austrian Alps by van Husen (1997) and to the two-fold LGM glacial advance in the eastern Southern Alps (Monegato et al., 2007; Rossato et al., 2013).

Nevertheless, new insights come from the recently drilled Torre Canavese core that crossed all the preserved glacigenic sequence in the right sector of the IMA. The radiocarbon dating (Ion Beam Laboratory, ETH Zürich) and the palynological analysis (CNR-IDPA, in progress) are going to strongly revise the stratigraphy of the more recent part of the IMA. In detail, the still now available radiocarbon dating in the Torre Canavese core results in a Holocene age for the upper part of the lacustrine succession covering the Serra subglacial till and in a pre-LGM age for the top of the lacustrine sequence below the till. These preliminary data indicate a likely LGM age for the Serra till, but this should be supported by a high-resolution palynological analysis (in progress) and further dating of the lower part of the upper lacustrine sequence. Combining these results with the pre-LGM ^{10}Be exposure ages of the erratics from the outermost Serra moraines, the Serra synthem should be subdivided into an External Serra unit, correlated to the MIS 6 glacial, and into an Internal Serra unit, referable to the MIS 2 glacial and so corresponding to the LGM maximum expansion of the Dora Baltea Glacier.

Many other elements suggest a LGM age for the Internal Serra unit:

- the notable thickness of the upper subglacial till body (13 m) in the Alice Superiore core best fits with the presence of more than one unit above the interstadial peat layer at 52 m depth: so besides Piverone unit also a part of the Serra synthem (Internal Serra unit) should constitute the upper glacigenic sequence if the peaty layer is referred to MIS 5c (Fig. 14). On the other hand, all the Serra synthem rests above the peaty layer if this is referred to MIS 7c interstadial.
- the Piverone unit has the same distribution of the Internal Serra unit (Fig. 7).
- the Piverone unit deposits and morphology (kame terraces and low discontinuous moraines) are typical of a recessional/cataglacial succession: so it could correspond to a recessional phase following to an acme phase, i.e. the Piverone unit in continuity with the Internal Serra unit.
- the Internal Serra and Piverone proglacial outwash deposits sharply intersect the External Serra (and Magnano) moraines (Fig. 7).
- the soils present over the Internal Serra, Piverone and Andrate moraines show a 10YR hue color and only their colluvium reaches a more evolved 7.5YR color. This feature requires further study.
- a palaeosol was found under a very thin glaciofluvial gravels cover at the top of the high proglacial plain South of Villareggia (Gianotti & Comina, 2012). This situation is better explained with an LGM age of the gravels and consequently with an LGM age for the Internal Serra moraines upstream.

- the subglacial deformation of the glacigenic sequence cropping out in the Rio Rudo incision (see 5.14) seems better explained with an LGM glacier very expanded outwards, i.e. until the outer edge of the Internal Serra unit.

If these working hypotheses will be confirmed, a wide extent of the glacier in the last glaciation should be indicated in the IMA, much larger than considered before (Fig. 6D). In the IMA left lateral sector this new interpretation fits well with the stratigraphy proposed by Gabert (1962).

9. CONCLUSION

An updated review of the geomorphology and stratigraphy of the Ivrea Morainic Amphitheatre is reported. Nine synthems attributed to the same number of major glaciations ranging from the end of the Early Pleistocene to the Late Pleistocene were recognized and mapped.

The Mongrando, Bornasco, Montino, Zubiena, Parogno, Torrazzo, Magnano, Serra, Piverone and Ivrea synthems occur from the oldest to the more recent unit. The outermost Mongrando synthem is referable to a Lower Pleistocene glaciation (MIS 22 or 20) and the innermost Ivrea synthem to MIS 2 corresponding to the last glaciation (LGM).

The more ancient and weathered sequence (2.5YR pedogroup A) can be differentiated into the Mongrando, Bornasco, Montino and Zubiena synthems. The intermediate 5YR pedogroup B comprises the Parogno and Torrazzo synthems. All this sequence coincides with the Mindel moraines or with the San Michele-Borgo group. Three glacial units (Magnano, Serra and Ivrea synthems) are distinguished into the more recent and less weathered deposits (pedogroup C 7.5YR). Magnano and Serra synthems coincide with the previous Riss moraines (or the Serra d'Ivrea group), while the last Ivrea synthem corresponds to the Würm or to the Bollengo-Albiano group.

The Mongrando and Bornasco synthems are separated by the Bosa palaeosol; the Bornasco and Montino synthems by the Sorgente Solfurea peaty layer; the Montino and Zubiena synthems by the Cascina Comunità palaeosol; the Parogno and Torrazzo synthems by the Cascina Gianetto gyttja layer; the Serra and Piverone by the peat layer in the Alice Superiore core. On the contrary, the distinction between Zubiena and Parogno synthems, between Parogno and Magnano synthems and between Magnano and Serra synthems is made on pedostratigraphical basis.

Detailed palynologic analysis will be necessary to better constrain the glacigenic sequences through the characterization of identified organic levels, which are used as stratigraphic markers (interglacial, interstadial or stadial), and their correlation to well-known biostratigraphical sequences. In detail, they are the Sorgente Solfurea peat layer, the Cascina Gianetto gyttja layer (tentatively referred to MIS 11.3), the Alice Superiore core peat layer (MIS 7c or MIS 5c); the Torre Canavese lacustrine sequences (work in progress) and the Rio Rudo organic-rich layer.

The Ivrea synthem is constrained by exposure and radiocarbon ages into thirteen principal subsynthems referable to glacial stadials of LGM-Lateglacial: seven stadials in amphitheatre (namely, the Piverone acme stadial, the Palazzo, Andrate, Pavone, Bienca, Prà San Pietro, and Germano stadials) and six stadials in the Aosta Valley (Torredaniele and Bard in the lower valley; Châtillon, Chambave/Fenis and Saint-Pierre in the middle valley; Courmayeur and Planpincieux in the high valley). The exposure ages of 23.8±1.7 ka (Ivrea6) and 20.1±3.0 ka (Ivrea1) from two erratic boulders on the Ivrea Hills provide a minimum age for final retreat of the Dora Baltea Glacier from the Ivrea Morainic Amphitheatre.

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REFERENCES

Adorno G. (1989) - Idrogeologia ed idrogeochimica dell'Anfiteatro Morenico d'Ivrea ad Est della Dora Baltea. Degree thesis, University of Turin.

Agassiz L. (1840) - Études sur les glaciers. Jent et Gasmann, Neuchatel.

Arobba D., Calderoni G., Caramiello R., Carraro F., Giardino M. & Quagliolo P. (1997) - Palynological and radiometric evidence of a last glacial-interstadial from peat sediments in the Ivrea morainic amphiteatre (NW-Italy). Geologia Insubrica 2(2), 143-148.

Baio M., Gianotti F. (1996) - Studio geologico e giacimentologico dell'area della "Bessa" (Biella, Italia). Geologia Insubrica, 1(1-2), 29-48.

Balco G., Briner J., Finkel R.C., Rayburn J.A., Ridge J.C. Schaefer J.M. (2009) - Regional beryllium-10 production rate calibration for northeastern North America. Quaternary Geochronology, 4, 93-107.

Balco G., Stone J.O., Lifton N.A., Dunai T.J. (2008). A complete and easily accessible means of calculating surface exposure ages or erosion rates from Be-10 and Al-26 measurements. Quaternary Geochronology, 3, 174-195.

Barbieri F., Carraro F., Petrucci F. (1974) - Osservazioni micropaleontologiche e stratigrafiche sulla serie marina e glaciomarina della Valchiusella (Ivrea, prov. di Torino). Acta Nat. Ateneo Parmense, 10(1), 5-14.

Baretti M. (1877) - Studi geologici sul Gruppo del Gran Paradiso. Atti. R. Acc. Lincei, 3(1), 122 pp., 7 tavv., Roma.

Basilici G., Martinetto E., Pavia G., Violanti D. (1998) - Paleoenviromental evolution in the Pliocene marine-

coastal succession of Val Chiusella (Ivrea, NW Italy). Boll. Soc. Paleont. It., 36(1-2), 23-52.
Biino G., Compagnoni R. (1989) - The Canavese Zone between the Serra d'Ivrea and the Dora Baltea River (Western Alps). Eclogae geol. Helv., 82, 413-427.
Bortolami G., Carraro F., Friz C., Govi M., Sacchi R. (1966) - Foglio 43 "Biella" della Carta Geologica d'Italia alla scala 1:100.000. II ed., Serv. Geol. It., Roma.
Bowen D.Q. (1978) - Quaternary Geology: A stratigraphic framework for multidisciplinary work. Pergamon Press, Oxford, pp. 221.
Brugiapaglia E. (2001) - Le lac de Villa : un site clé pour l'histoire de la végétation terdiglaciaire et holocène en Vallée d'Aoste (Italie). Revue Valdôtaine Hist. Nat., 55, 55-72.
Bruno L. (1877) - I terreni costituenti l'anfiteatro allo sbocco della Dora Baltea. Tip. F.L. Curbis, Ivrea, 65 pp.
Caramiello R., Carraro F., Collo G., Gianotti F., Giardino M., Martinetto E., Perotto A., Siniscalco C. (1996) - Revisione del significato dei depositi "villafranchiani" in Piemonte. Il Quaternario, Italian J. Quat. Sci., 9 (1), 187-194.
Carraro F. (1992) - La zona pedemontana da Ivrea ad Arona. Depositi quaternari. In: Dal Piaz G. V. (ed.), Le Alpi dal Monte Bianco al Lago Maggiore. Soc. Geol. It., Guide Geologiche Regionali, 3(a), 186-209, BEMA, Milano.
Carraro F., Ed. (1996) - Revisione del Villafranchiano nell'area-tipo di Villafranca d'Asti. Il Quaternario, Italian J. Quat. Sci., 9(1), 5-120.
Carraro F. (1998) - The problem of the "Pliocene glaciomarine deposits of Val Chiusella": state of the art. In Martinetto E. (ed), Pliocene Plants, Environments and climate of North-Western Italy. Guide to the field conference: 41-44. Mottalciata, april 27-30th. Dip. Scienze della Terra, Univ. Studi Torino, 85 pp.
Carraro F., Fontan D., Gianotti F., Pennacchioni G., Ravello M., Schiavo A., Tartarotti P., Venturini G., Vuillermoz R. (2012) - 89 Courmayeur Sheet, Geologic Map of Italy at the 1:50,000 scale. ISPRA - Servizio Geologico d'Italia.
Carraro F., Lanza R., Perotto A., Zanella E. (1991) - L'evoluzione morfologica del Biellese occidentale durante il Pliestocene inferiore e medio, in relazione all'inizio della costruzione dell'Anfiteatro Morenico d'Ivrea. Boll. Museo Reg. Sc. Nat. Torino, 9(1), 99-117.
Carraro F., Medioli F., Petrucci F. (1974) - Significato della presenza di depositi glaciomarini nell'Anfiteatro Morenico d'Ivrea riguardo al problema del limite Plio-Pleistocene. Acc. Naz. Lincei, Rend. Cl. SFMN., Serie 8, 56(3), 397-402, Roma.
Carraro F., Medioli F., Petrucci F. (1975) - Geomorphological study of the Morainic Amphitheatre of Ivrea, Northwest Italy. Bull. R. Soc. New Zealand, 13, 89-93. Wellington.
Carraro F., Petrucci F. (1969) - Carte Géologique de la Plaine du Piémont 1:400.000. VIII Congrés INQUA, Paris.
Cerchio E. (1980) - Studio palinologico dei depositi glaciomarini pliocenico-medi della Val Chiusella. Degree Thesis, University of Torino, 113 pp.
Claude A., Ivy-Ochs S., Kober F., Antognini M., Salcher B., Kubik P.W. (2014) - The Chironico landslide (Valle Leventina, southern Swiss Alps): age and evolution. Swiss Journal of Geosciences, 107(2/3), 273-291.
Colombero C., Comina C., Gianotti F., Sambuelli L. (2014) - Waterborne and on-land electrical surveys to suggest the geological evolution of a glacial lake in NW Italy. Journal of Applied Geophysics, 105, 191-202.
Compagnoni R., Dal Piaz G.V., Hunziker J.C., Gosso G., Lombardo B., Williams P.F. (1977) - The Sesia-Lanzo zone, a slice of continental crust with Alpine high pressure-low temperature assemblages in the Western Italian Alps. Rend. Soc. It. Min. Petr., 33, 281-334.
Dal Piaz G.V., Baggio P., Bertolo D., Bistacchi A., Carraro F., Fontan D., Gianotti F., Martin S., Monopoli B., Pennacchioni G., Polino R., Schiavo A., Tartarotti P., Venturini G. (2010) - 91 Châtillon Sheet, Geologic Map of Italy at the 1:50,000 scale. ISPRA - Servizio Geologico d'Italia.
Dal Piaz G.V., Bistacchi A., Massironi M. (2003) - Geological outline of the Alps. Episodes, 26(3), 175-180.
De Giusti F., Dal Piaz G.V., Massironi M., Schiavo A. (2004) - Carta geotettonica della Valle d'Aosta. Memorie Scienze Geologiche, Padova, 55, 129-149.
Dela Pierre F., Piana F., Boano P., Fioraso G., Forno M.G., Polino R., Clari P. (2003a) - 157 Trino Sheet, Geologic Map of Italy at the 1:50,000 scale. APAT, Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici - Dipartimento Difesa del Suolo, Roma.
Dela Pierre F., Piana F., Fioraso G., Boano P., Bicchi E., Forno M.G., Violanti D., Balestro G., Clari P., d'Atri A., De Luca D., Morelli M., Ruffini R. (2003b) - Note Illustrative della Carta Geologica d'Italia alla scala 1:50,000, Foglio 157 Trino. APAT, Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici-Dipartimento Difesa del Suolo, Roma, 147 pp.
Ehlers J., Gibbard P.L. (Eds.) (2004a) - Quaternary Glaciations - Extent and Chronology, Part I: Europe. Developments in Quaternary Science, vol. 2a. Elsevier, Amsterdam.
Ehlers J., Gibbard P.L. (Eds.) (2004b) - Quaternary Glaciations - Extent and Chronology, Part II: North America. Developments in Quaternary Science, vol. 2b. Elsevier, Amsterdam.
Ehlers J., Gibbard P.L. (Eds.) (2004c) - Quaternary Glaciations - Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica. Developments in Quaternary Science, vol. 2c. Elsevier, Amsterdam.
Elter G. (1987) - Carte géologique de la Vallée d'Aoste, échelle 1:100.000. Centro di Studio sui problemi dell'orogeno delle Alpi Occidentali, C.N.R. Torino, SELCA Firenze.
Emiliani C. (1955) - Pleistocene temperatures. Journal of Geology, 63, 538-578.
Fontana A., Monegato G., Devoto S., Zavagno E., Burla I., Cucchi F. (2014) - Evolution of an Alpine fluvioglacial system at the LGM decay: the Cormor megafan (NE Italy). Geomorphology, 204, 136-153.

Forno M. G., Gattiglio M., Comina C., Barbero D., Bertini A., Boano P., Doglione A., Irace A., Gianotti F., Martinetto E., Mottura A., Sala B. (in press) - Stratigraphic notes on the the type-area and Castelnuovo don Bosco villafranchian succession (Asti Reliefs, Piedmont). Alpine and Mediterranean Quaternary, 27 (1).

Forno M.G., Gianotti F. (2005a) - Arrêt 1. Serra d'Ivrea et Petite Serra (Andrate). Arrêt 2. Stratigraphie de la Serra d'Ivrea (Chiaverano). In: P. Deline, M. Giardino, G. Nicoud (Eds), Le Quaternaire des vallées alpines. Collection EDYTEM, Cahiers de Géographie, 3, 137-143, Chambéry.

Forno M.G., Gianotti F., Grosso F. (2005b) - Arrêt 3. Les Collines d'Ivrea. Affleurements rocheux à modelé glaciaire à l'intérieur de l'AMI. In: P. Deline, M. Giardino, G. Nicoud (Eds), Le Quaternaire des vallées alpines. Collection EDYTEM, Cahiers de Géographie, 3, 144-146, Chambéry.

Forno M.G., Gianotti F., Grosso F., Pini R. (2007) - Stratigrafia della sequenza cataglaciale nei colli di Ivrea e dati pollinici preliminari sui depositi lacustri di Chiaverano (Torino). Il Quaternario, Italian Journal of Quaternary Sciences, 20(2), 213-228.

Forno M.G., Gianotti F., Racca G. (2010) - Significato paleoclimatico dei rapporti tra il glacialismo principale e quello tributario nella bassa Valle della Dora Baltea. Il Quaternario, Italian Journal of Quaternary Sciences 23(1), 105-124.

Forno M.G., Lucchesi S. (2005) - La successione fluviale terrazzata pleistocenica dei versanti occidentale e nordoccidentale della Collina di Torino. Il Quaternario It. Journ. Quatern. Sc., 18(2), 123-134.

Franchi S., Mattirolo S., Novarese V., Stella A., Zaccagna D. (1908) - Carta Geologica delle Alpi Occidentali alla scala 1:400 000. R. Uff. Geol. It., Roma.

Franchi S., Mattirolo S., Novarese V., Stella A. (1912) - Foglio 42 "Ivrea" della Carta Geologica d'Italia alla scala 1:100.000. I ed., R. Uff. Geol. It., Roma.

Franchi S., Stella A. (1933) - Foglio 43 "Biella" della Carta Geologica d'Italia alla scala 1:100.000. I ed., R. Uff. Geol. It., Roma.

Gabert P. (1962) - Les plaines occidentales du Po e leurs piedmonts (Piémont, Lombardie occidentale et centrale). Etude morphologique. Imp. Louis-Jean, Gap, pp. 531.

Gianotti F. (1993) - Ricostruzione dell'evoluzione quaternaria del margine esterno del settore laterale sinistro dell'Anfiteatro Morenico d'Ivrea. Degree thesis, University of Turin.

Gianotti F. (1996) - Bessa. Paesaggio ed evoluzione delle grandi aurifodine biellesi. Quaderni di Natura Biellese, pp. 83, Eventi e Progetti Editore, Vigliano Biellese.

Gianotti F. (2007) - Stratigrafia dell'Anfiteatro Morenico di Ivrea. Ph.d Thesis, University of Turin, pp. 270.

Gianotti F. (2011) - Geological setting of the Pleistocene placers and roman gold mines of the Ivrea Morainic Amphitheatre (Piedmont, NW Italy). Ext. Abstracts Convegno AIQUA "Il Quaternario italiano. Conoscenze e prospettive", Roma, 24-25 febbraio 2011, Il Quaternario, Italian Journal of Quaternary Sciences, 24(2), 183-185.

Gianotti F., Comina C. (2012) - Inquadramento geologico e prime indagini geofisiche e stratigrafiche sul sito di Borgo Nuovo di Dora, borgo franco medievale abbandonato presso Villareggia (TO). In: Panero F. & Pinto G., Assetti territoriali e villaggi abbandonati (secoli XII-XIV), CISIM, Off. Grafiche Comun., Bra, 309-320.

Gianotti F., Forno M.G., Ivy-Ochs S., Kubik P.W. (2008) - New chronological and stratigraphical data on the Ivrea Amphitheatre (Piedmont, NW Italy). Quaternary International, 190, 123-135.

Gianotti F., Pini R. (2011) - Stratigraphical subdivision of the Middle Pleistocene glacigenic sequence of the Ivrea amphitheatre (Piedmont, NW Italy). Abstracts XVIII INQUA Congress Bern 2011, 21-27 July, Quaternary International, 279-280.

Gibbard P.L., Boreham S., Cohen K.M., Moscariello A. (2005). Global chronostratigraphical correlation table for the last 2.7 million years. Boreas, 34(1) (unpaginated).

Giraudi C. (2014) - Quaternary studies as a tool to validate seismic hazard potential of tectonic structures: the case of the Monferrato Thrust Front (Vercelli Plain, NNW Italy). Alpine and Mediterranean Quaternary, 27(1), 5-28.

Heyman J. (2014) - Paleoglaciation of the Tibetan Plateau and surrounding mountains based on exposure ages and ELA depression estimates. Quaternary Sciences Review, 91, 30-41.

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 10Be, 26Al, 36Cl, and 21Ne. Geological Society of America Special Paper 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. Jour. Quat. Sc., 23, 559-573.

Kukla G.J. (1977) - Pleistocene Land-Sea Correlations. 1. Europe. Earth Science Review, 13, 307-374.

Lisiecki L.E., Raymo M.E. (2005) - A Pliocene-Pleistocene stack of 57 globally distributed benthic $d^{18}O$ records. Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071

Lyell C. (1833) - Principles of Geology, being an attempt to explain the former changes of the earth' s surface, by reference to causes now in operation. 3 voll., J. Murray, London.

Marco C. (1892) - Studio geologico dell'anfiteatro morenico d'Ivrea. Tipografia Garda, Ivrea, 62 pp., 2 tt, prof. 1:25.000, Roux, Torino.

Marcuzzi A. (2007) - Ricostruzione dell'evoluzione geologica plio-quaternaria di parte del settore laterale sinistro dell'anfiteatro morenico d'Ivrea. Degree thesis, University of Turin.

Martinetto E. (ed.) (1998) - Pliocene Plants, Environments and climate of North-Western Italy. Guide to the field conference: 39-53. Mottalciata, april 27-30th. Univ. Studi Torino, pp. 85.

Martins C., Gastaldi B. (1850) - Essai sur les terrains superficiels de la vallée du Pô, aux environs de Tu-

rin, comparés a ceux de la plaine suisse. Bull. Soc. Gèol. France, ser. 2, 7, 554-605.
Monegato G., Ravazzi C., Donegana M., Pini R., Calderoni G., Wick L. (2007) - Evidence of a two-fold glacial advance during the last glacial maximum in the Tagliamento end moraine system (eastern Alps). Quaternary Research 68, 284-302.
Muttoni G., Carcano C., Garzanti E., Ghielmi M., Piccin A., Pini R., Rogledi S., Sciunnach D. (2003) - Onset of major Pleistocene glaciations in the Alps. Geology 31(11), 989-992.
Muttoni G., Ravazzi C., Breda M., Pini R., Laj C., Kissel C., Mazaud A., Garzanti E. (2007) - Magnetostratigraphic dating of an intensification of glacial activity in the southern Italian Alps during Marine Isotope Stage 22. Quaternary Research, 67, 161-173.
Penck A. , Bruckner E. (1909) - Die Alpen Im Eiszeitalter. Volume 3: 761-768. Chr. Herm. Tauchnitz, Leipzig.
Penck A., Bruckner E., du Pasquier (1894) - Le Système glaciaire des Alpes. Guide Congr. Géol. Int., Zurich., Bull. Soc. Sc. Nat. Neuchatel, 22, pp. 86, 17 ff.. Estratto (1894): Imprimerie de H. Wolfrath & C., Neuchatel.
Pini R., Ravazzi C., Donegana M. (2009) - Pollen stratigraphy, vegetation and climate history of the last 215 ka in the Azzano Decimo core (plain of Friuli, north-eastern Italy). Quaternary Science Reviews, 28, 1268-1290.
Porter S. C., Orombelli G. (1982) - Late-Glacial ice advances in the Westwrn Italian Alps. Boreas, 11, 125-140.
Rossato S., Monegato G., Mozzi P., Cucato M., Gaudioso B., Miola A. (2013) - Late Quaternary glaciations and connections to the piedmont plain in the prealpine environment: The middle and lower Astico Valley (NE Italy). Quaternary International, 288, 8-24.
Sacco F. (1888) - I terreni terziari e quaternari del Biellese. 16 pp., 1 geol. map 1:100.000, Guadagnini e Candellero, Torino.
Sacco F. (1927a) - Schema geologico del Biellese. Il Biellese, Ivrea.
Sacco F. (1927b) - Il glacialismo nella Valle d'Aosta. 66 pp., 2 carte 1.100.000, Min. LL. PP., Uff. Idrog. Po.
Sacco F. (1938) - Il Glacialismo Piemontese. L'Universo, 16, 217-231 and 337-352, Firenze.
Salvador A. (ed.) (1994) - International Stratigraphic Guide. A guide to stratigraphic classification, terminology and procedure (2nd Ed.). International Union of Geological Sciences, Trondheim, Norway, and The Geological Society of America, Boulder, Colorado, pp. 214.
Scardia G., Donegana M., Muttoni G., Ravazzi C., Vezzoli G. (2010) - Late Matuyama climate-driven alluvial fan progradation at the Alpine southern foothills. Quaternary Science Review, 29, 832-846.
Schlüchter C. (2004) - The Swiss glacial record - a schematic summary. In Ehlers J. and Gibbard P.L. (Eds.), Quaternary Glaciations - Extent and Chronology, Part I: Europe, 413-418.
Schneider R.E. (1978) - Pollenanalytische Untersuchungen zur Kenntnis der Spät-und postglazialen Vegetationsgeschischte am Südrand der Alpen zwischen Turin und Varese (Italien). Bot. Jahrb. Syst., 100(1), 26-109.
Shackleton N.J. (1967) - Oxygen isotope analyses and paleotemperatures re-assessed. Nature, 215, 15-17.
Shackleton N.J., Opdyke N.D. (1973) - Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific cores V28-238: oxigen isotope temperatures and ice volumes on a 105 year - 106 year scale. Quaternary Research, 3, 39-55.
Sibrava V., Bowen D.Q., Richmond G.M. (eds.) (1986) - Quaternary glaciations in the Northern Hemisphere. Quaternary Science Reviews, 5, 171-180.
Stoppani A. (1880) - L'Era Neozoica. In Negri G, Stoppani A., Mercalli G., Geologia d'Italia. Vallardi, Milano.
Studer (1844) - Lehrbuch der physikalischen Geographie und Geologie. Vol. 1 , Chur und Leipzig, Bern.
van Husen D. (1997) - LGM and Late-glacial fluctuations in the Eastern Alps. Quaternary International 38/39, 109-118.
Venturini G. (1995) - Geology, geochemistry and geochronology of the inner central Sesia Zone (Western Alps, Italy). Mém. Géol. Lausanne, 25, pp.148.
Zienert A. (1970) - Das Moränen-Amphitheater von Ivrea (Dora Baltea). Heidelberger Geogr. Arb., 38, 141-157.
Zingg A., Handy M. R., Hunziker J. C., Schmid S. M. (1990) - Tectonometamorphic history of the Ivrea zone and its relationship to the crustal evolution of the Southern Alps . Tectonophysic, 182, 169-182.

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