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THE EARLY AND MIDDLE PLEISTOCENE GLACIATIONS IN THE ALPS

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ABSTRACT: The Alps experienced extensive glaciations during many Pleistocene cold stages. New stratigraphic and geochronological data gathered in the last decade depict the Early Pleistocene glaciations and their record is continuously updated. The onset of major glaciations since the late Matuyama Chron (MIS 22-20) is better recognized in many end moraine systems along the southern side of the Alps. The updated chronology of the Middle Pleistocene phases indicates an improvement of the knowledge about the penultimate glaciation (MIS 6) and the evidence that every sector has had its own most extensive glaciation in a different time span. The dissimilar architecture of the end moraine systems suggests a different behavior of the glaciers from one cold stage to the others. The development of the largest glacier networks with associated piedmont lobes (i.e., Adige, Adda and likely Inn) required abundant snow supply promoted by the southerly circulation, like in the LGM. For the systems with the highest accumulation areas (i.e., Valais, Dora Baltea, Rhine-Reuss and Ticino-Toce) a larger number of glacial units was recorded likely because these were more sensitive to every circulation regime impacting the Alps, whether northwest or south dominated. The Alps remain the most studied mountain range with respect to Quaternary glaciations, thereby providing a unique and valuable resource.

Keywords: Quaternary glaciations, european Alps, Early-Middle Pleistocene, palaeomagnetism, glacigenic deposits.

1. INTRODUCTION

The European Alps (Fig. 1) have been the key site for the development of the idea of multiple Quaternary glaciations since the milestone work of Penck & Brückner (1901-1909). The study of the glacial history of the Alps began earlier, in the XIX century (e.g., Agassiz, 1840; Morlot, 1854; Omboni, 1861; de Mortillet, 1861; Gastaldi, 1865; Taramelli, 1875; Sacco, 1887; Mühlberg, 1896; Wannier, 2023), and since that time this mountain range has represented a major field laboratory for new theories and methodological advances in glacial stratigraphy and geochronology. The Alpine terminal moraine systems, also known as morainic amphitheaters, occur at the outlet of the major Alpine valleys and are primary sites for the study of Quaternary glaciations (Penck et al., 1894) and developing one of the major knowledge advance in Quaternary studies (Orombelli et al., 2023). Their morphostratigraphic architecture was studied by Penck & Brückner (1901-1909), who defined four climatostratigraphic units and correlated them across the Alps. Accordingly, this study gave birth to a new paradigm in ice age history of the Earth: four Alpine glaciations (from older to younger: Günz, Mindel, Riss, and Würm) and the intervening "interglacials". Their definition based on glacial sequences consisting of terminal moraines and proglacial outwash terraces stands as a milestone in geoscientific research, not only for the Alps but also for elsewhere in Eurasia (e.g., Krūkle & Stelle, 1964; Grosswald et al., 1994; Lehmkuhl et al., 2011) and worldwide (Cotton, 1963). For a long time, definition and correlation of the glacial and glaciofluvial deposits were mostly made by combining the weathering degree and geomorphological evidence (e.g. the altitudinal concordance of the distribution of glaciofluvial terraces), where topographic elevation is a key for a relative stratigraphic framework (e.g., Bini, 1997).

Subsequent stratigraphic studies, since the 1970s, focused on facies analysis and bounding surfaces, leading to the identification of important discontinuities (including buried soils and interglacial/interstadial peat layers), casting new light on the age of old glaciations and questioning the reliability of the four glaciations paradigm (Bowen, 1978; Billard & Orombelli, 1986; Schlüchter, 1981; 1986). Based on marine and ice cores, the development of the Marine Isotope Stage (MIS) stratigraphy documented up to fifty cold stages (Shackleton & Pisias, 1985; Lisieki & Raymo, 2005) during the Pleistocene (*sensu* Gibbard et al., 2010) raising the question if and how the four-glaciation model

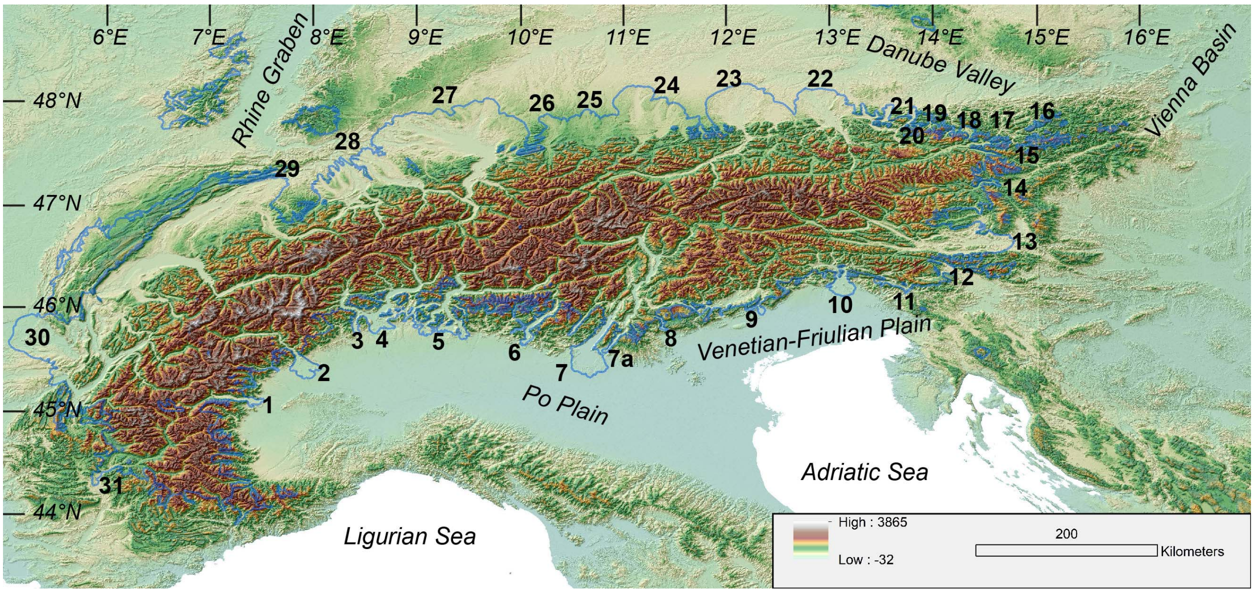

Fig. 1 - Reference areas for the Alpine Pre-LGM glaciation in the European Alps. Main glacier catchments numbered as in Tab. 1.

could have been applicable (e.g., Billard & Derbyshire, 1985; Šibrava et al., 1986; Billard & Orombelli, 1986; Schlüchter, 1988). With this change of perspective, in the Alps, a minimum of 15 different glacier advances were then recognized in the Swiss Foreland (Preusser et al., 2011; Schlüchter et al., 2020), and about 11 in the central southern foreland sectors (Bini et al., 2014; Gianotti et al., 2015). Among these, 13 and 7 respectively, are ascribable to the Early and Middle Pleistocene (Schlüchter et al., 2020; Ivy-Ochs et al., 2022). Considering the lack of chronostratigraphic information for many Early-Middle Pleistocene glacial units (Hughes et al., 2020) and their geographical distribution we can pose several questions, such as: how many glacier advances could have been recorded in the circum-Alpine area? Which were the major ones (i.e. foreland reaching)? Did Alpine glaciers have comparable extents in each cold phase?

The Alps were also the playground for testing new geochronological tools during the last three decades, leading to several attempts to place the glacier advances within the framework of marine isotope stages, also considering the ongoing uplift of the Alps (Champagnac et al., 2007; Scardia et al., 2006; 2012; Sternai et al, 2019). Moreover, the remarkable regional dissimilarities in term of number of glacier advances from one sector to another (Ivy-Ochs et al., 2022), reflect the differences in the morphological and sedimentary archives, due to variations in tectonic regimes (uplift vs. subsidence), accommodation space, and preservation potential. Such conditions have an impact on the choice of suitable stratigraphic approach (litho-, morpho-, allostratigraphy) and in most cases also on the terminology of glaciations (chronostratigraphy, climatostratigraphy). This demands the development of new approaches in order to disentangle the stratigraphic puzzle, and its meaning in terms of paleoclimate vs. tectonic evolution of the Alps. Apart from the Late Pleistocene advances, encompassing the Würm (Chaline & Jerz, 1984; Monegato & Ravazzi, 2018), the Early and Middle Pleistocene glacial units still need further investigation. The present review is aimed at describing the architecture of Early to Middle Pleistocene glacial units across the Alps and discussing the major questions related to their distribution.

2. BACKGROUND STUDIES

As the cradle of the Quaternary glaciation concept, the Alps have a long-lasting history of studies concerning when and how mountain glaciers became a vast ice field during the Pleistocene. The moraine amphitheaters in the piedmont area at the outlet of the major Alpine valleys have been the site for countless studies since the early researches and also today represent key areas for reconstructing Alpine glaciations. Starting from the pioneering works by Venetz (1833), Agassiz (1840) and de Charpentier (1841), in which the idea of glaciers reaching the lowlands was developed, a large number of scholars examined in depth the glacial landforms and deposits all around the Alps. At the beginning, a single cold phase was assumed for the deposition of the moraines (e.g., Venetz, 1833; Martins & Gastaldi, 1850; Bruno, 1877) on the basis of lithostratigraphical description, including the outwash deposits. However, very soon evidence for multiple glaciations was reported from the Lake Geneva area (Morlot, 1854), the Swiss Alpine forelands (Mühlberg, 1896), the Northern foreland (e.g., Penck, 1882; Blaas, 1884; Penck et al., 1894) (Fig. 2A), and the southern Alpine foreland (Nicolis, 1899; Capeder, 1904). With their milestone work, Penck & Brückner (1901-1909) described different suites of gravel accumulation that were connected upstream to moraines (Fig. 2C), recognizing four glaciations all across the circum-Alpine area (Fig. 2B). The four fold glaciation paradigm was, after its publication, quickly accepted and applied in regional studies and maps. Some authors added more “glaciations” to the list according to older gravel accumulation suites (Eberl, 1930; Schaefer, 1956; Schreiner & Ebel, 1981; Glückert, 1974; Doppler et al., 2011) or split the four glaciations into subunits (e.g., Venzo, 1965, 1977; Carraro et al., 1970). This fact created some ambiguities in correlating glacial/glaciofluvial units from one site to another, even if contiguous. The new field surveys, based on the allostratigraphic approach, revealed these differences by the difficulty of tracing lateral boundaries (e.g., Bini et al., 2004a, 2004b, 2015), which led to a splitting of the regional Alpine stratigraphy into local, independent stratigraphic frameworks over the Swiss and Italian sectors (e.g., Preusser et al., 2011; Graf & Burkhalter, 2016; Fioraso et al., 2021; Ivy-Ochs et al., 2022, and references therein). On the other hand, in the German-Austrian area, the Penck & Brückner (1901-1909) subdivision has been maintained because of the physical correlation of glaciofluvial terraces in the piedmont area and along the further catchment of the Danube River (Ellwanger et al., 2011; Doppler et al., 2011; Van Husen & Reitner, 2011a; Ivy-Ochs et al., 2022; Reitner, 2022).

Within the general architecture of the moraine suites in the circum-Alpine area thick sequences of conglomerates were also included, known as *Deckenschotter* (Cover Gravels in German) on the northern side of the Alps (Du Pasquier, 1891; Frei, 1912; Graf, 1993). In the southern side, coarse-grained gravel deposits, known as *Ceppo*, were partially ascribed to glaciofluvial sedimentation based on petrographic composition (e.g., Venzo, 1950; 1957).

The systematic and multidisciplinary study of several cores in the southern Alpine foreland yielded during the last two decades a more comprehensive framework for the onset of "major" glaciations and the mid-Pleistocene revolution (Muttoni et al., 2003, 2007; Scardia et al., 2006, 2010, 2012). Concurrently, the chronostratigraphy of the Swiss *Deckenschotter* in the northern Alpine Foreland was progressively improved with employment of new dating techniques all based on cosmogenic nuclides. These include the depth profile, burial and isochron-burial dating techniques, with the latter as well applying the P-PINI age calculation model (Akçar et al., 2014, 2017; Claude et al., 2017, 2019; Knudsen et al., 2020; Dieleman et al., 2022). This new *Deckenschotter* chronology outlines three major accumulation phases at ca. 2.5 Ma, ca. 1.5 Ma, and ca. 1 Ma (Fig. 3A-C).

3. GLACIATIONS AT THE PLIO-PLEISTOCENE BOUNDARY

The earliest evidence of Quaternary glaciation in the Northern Hemisphere is documented at the end of the Pliocene (ca. 2.7 Ma) by the first occurrence of ice-rafted debris in North Atlantic oceanic sediments (Thierens et al., 2012; Bailey et al., 2013). Terrestrial evidence is related to the earliest major waxing of the Laurentide Ice Sheet (LIS) at ca. 2.4 Ma and correlated with MIS 100 (Balco & Rovey, 2010). Data about the Alpine ice fields for that period are scarce (Batchelor et al., 2019), although the Alps had already achieved an elevation high enough to host large glaciers (e.g., Pignalosa et al., 2011; Kuhlemann & Rahn, 2013; Winterberg & Willett, 2019; Krsnik et al., 2021; Dieleman et al., 2022).

In the northern foreland, the gravel units at Stadlerberg and Irchel (Fig. 3B) in northern Switzerland represent the early phase of the *Deckenschotter* accumulation at 2.6 ±0.1 Ma (Claude et al., 2017; 2019; Dieleman et al., 2022). This is in agreement with the occurrence of *Mimomys* cf. *pliocaenicus* (Irchel site, Bolliger et al., 1996) which belongs to the Gelasian/Tiglian MN17 unit of the European Land Mammals Zones. These gravels are interpreted as glaciofluvial units, thus as evidence of an early extensive glaciation that occurred already by 2.6 Ma in the northern side the Alps. Actually the *Deckenschotter* sequence at Irchel is made of a number of different units, whose ages suggest a cut and fill evolution of the northern foreland during the Early Pleistocene (Dieleman et al., 2022). In the Swiss foreland an overall eight glaciations are suggested for the Early Pleistocene by Schlüchter et al. (2020), which should include the late Matuyama. The *Deckenschotter* is interpreted as the glaciofluvial sediments related to this time span also in the German sector of the Alpine foreland (*Älteste Deckenschotter* in German stratigraphy); there *Deckenschotter* is attributed to be the outwash deposition of Biber and Donau glaciations (Ellwanger et al., 2011; Doppler et al., 2011), notwithstanding some disagreements (see Fiebig et al., 2011). The first dating attempt of *Deckenschotter* in the German sector provided the age of $2.35^{+1.08}_{-0.88}$ Ma (Häuselmann et al., 2007) that could be considered quite comparable to the *Deckenschotter* chronology at Irchel despite the large analytic uncertainty.

In the western sector, evidence of cold stages is testified only by loess deposition along the Rhone Valley, south of Lyon (Bourdier, 1963) and biostratigraphically ascribed to 2.2 Ma (Guerin, 1980; Billard & Orombelli, 1986).

Around the Plio-Pleistocene boundary, the southern side of the Alps was characterized by transitional and marine deposits ("Villafranchian"; Carraro et al., 1996;), overlain by conglomerate (*Ceppo*) in the Lombardy sector (e.g., Nangeroni, 1940; Venzo, 1950; Orombelli, 1979; Zuccoli, 2000; Bini et al., 2004a). The former belongs to the Gelasian in the Adda sector based on palaevegetation (Venzo, 1950; Corselli et al., 1985; Pini et al., 2002) and in the Verbano sector (Bini et al., 1997). The first glacier advance is testified by Immacolata and Vivirolo formations in the Verbano sector and tentatively ascribed by magnetostratigraphy (Uggeri et al., 1997) to the Gauss-Matuyama geomagnetic reversal (2.58 Ma; Gradstein et al., 2020). Actually, the magnetostratigraphy presented by Uggeri et al. (1997) can be equally correlated to the Jaramillo - late Matuyama (C1r.1n-C1r.1r) reversal (0.99 Ma, see next section), and the associated glacigenic deposits could be ascribed to a late Matuyama glaciation. Lacking independent chronologic constraints, the age of the earliest glacigenic deposits in the Verbano sector remains an open issue. Conglomerate successions that mark the increase of sediment production and delivery are present in the Prealpine valleys from the Orobic to the Julian Alps and Prealps, some of them were ascribed to the Early Pleistocene by means of palaeobotanic content and stratigraphic relationships (Monegato & Stefani, 2011; Martinetto et al., 2012; Bini et al., 2015; Monegato

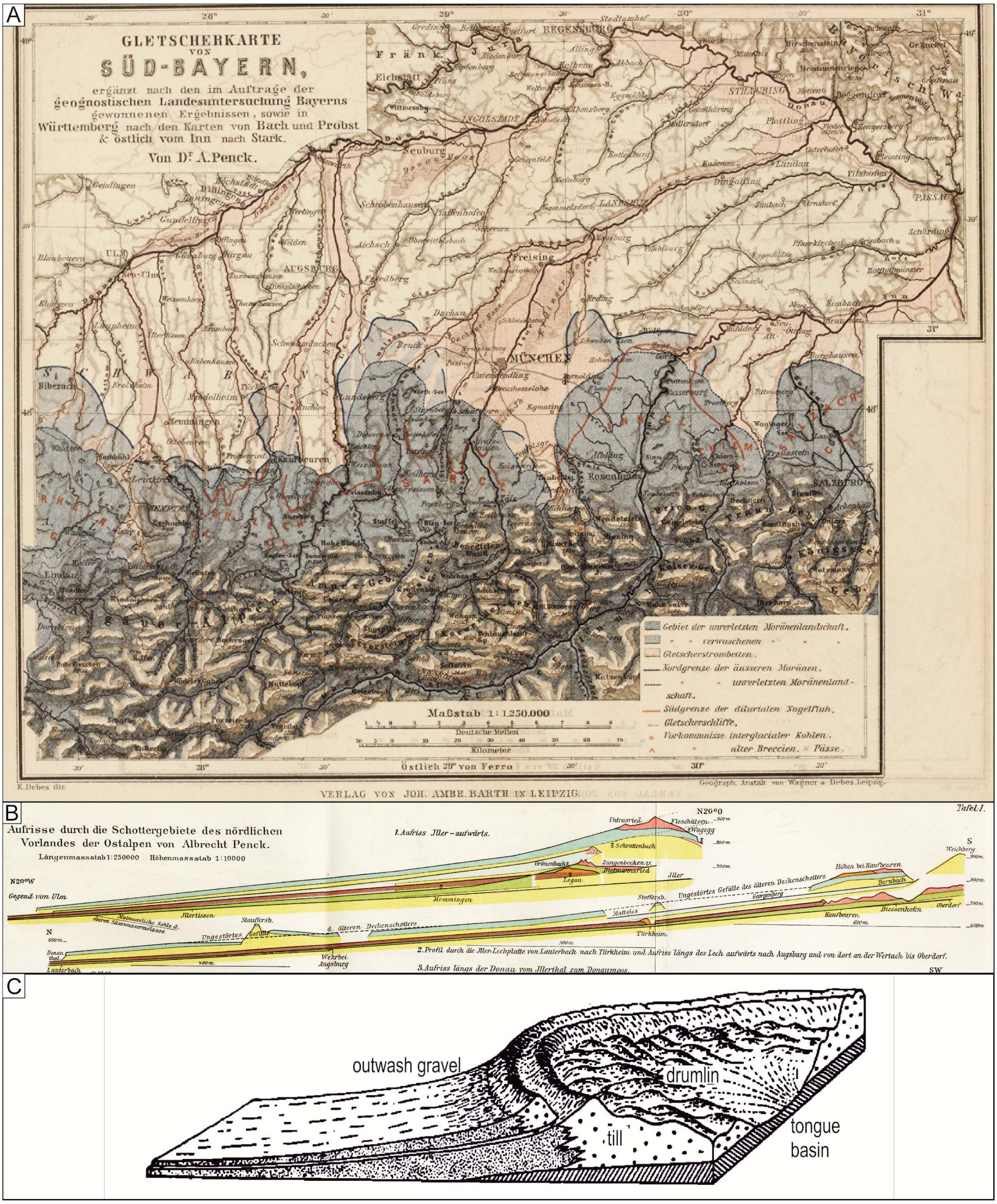

Fig. 2 - A) Map of the Southern Bavaria by Penck (1882) in which the Author depicted multiple glacial advances in the Alps; B) Cross sections correlating glacial units of the end moraine systems with glaciofluvial terraces in the northern foreland depicted by Penck and Brückner (1901-1909). C) Glacial sequence as defined by Penck & Brückner (1901-1909).

& Poli, 2015). A burial age to 1.86 ±0.19 Ma was provided in the Sava valley on conglomerate complex ascribed to glaciofluvial environment (Mihevc et al., 2015).

In the southern foreland, characterized by the transition to marine environments (Scardia et al., 2006; Garzanti et al., 2011), indications of cold phases triggering alluvial aggradation were detected in many sites through sediment core analysis (Ambrosetti et al., 1980; Ravazzi et al., 2005, 2009; Scardia et al., 2006; 2010; Bini et al., 2015). The *Ceppo* units were ascribed to glaciofluvial deposition during the Early Pleistocene (Bini, 1997).

According to the available data, glaciers could have developed during this period in the highest sectors of the Alps (Keller & Krayss, 2010; Preusser et al., 2011; van Husen & Reitner, 2011a) without directly reaching the foreland, but enhancing the development of widespread alluvial and braided systems at the outlets of Alpine valleys, because of the increased sediment supply and water discharges. Such processes enabled the formation of loess in the Alpine Foreland, as recorded in the loess archives of Stranzendorf, showing the onset of loess at the G/M boundary and Krems-Schießstätte starting with the Olduvai event (Fink et al., 1976; Fink & Kukla, 1977). Moreover, the occurrence of trunk valley glaciers is still debated as the carving of major valleys occurred later, starting from the late Matuyama (Häuselmann et al., 2007; Valla et al., 2011).

4. LATE MATUYAMA GLACIATIONS (MIS22-20)

According to Muttoni et al. (2003) the "major" glaciations in the southern side of the Alps started at about 0.9 Ma when extensive boreal ice sheets expanded (Batchelor et al., 2019; Greenwood et al., 2022). For "major" we mean a climatic stage which was cold and long enough to allow the glaciers to spread out from the main Alpine valleys, forming piedmont lobes in the foreland at both the sides of the mountain range.

In the northern foreland, the till interbedded with *Deckenschotter* at the Swiss Feusi site (Fig. 3A) was dated to 0.9 ±0.1 Ma with the P-PINI cosmogenic nuclide burial-dating model for glacial deposits (after Knudsen et al., 2020). In addition, two *Deckenschotter* sites attributed to the Steig Gravels (*sensu* Graf, 1993) at Irchel were dated to 0.9 ±0.2 and 1.3 ±0.1Ma using isochron-burial dating technique with cosmogenic ^{26}Al and ^{10}Be (Claude et al., 2019; Dieleman et al., 2022). In the German-Austrian foreland, the Lichtenegg diamicton (Menzies & Ellwanger, 2010; Ellwanger et al., 2011) and the fine-grained deposits intercalated with the glacial till at Pfullendorf (Bibus et al., 1996; Doppler et al., 2011) were ascribed to the Early Pleistocene based on reverse polarity. Fluvial deposits related to the *Älterer Deckenschotter* (Older Cover Gravels) (Ellwanger et al., 1995, 2011) at Altheiligenberg showed reverse polarity (Fromm, 1989). The covering loess of the *Hohere Älterer Deckenschotter* (Upper Older Cover Gravels) at Zusamplatte (Ausburg) recorded the B/M reversal (Doppler et al., 2011); the glaciofluvial deposits were ascribed to the Early Pleistocene also for the presence of Tiglian mammal fauna (Königswald & Heinrich, 2007). The same attribution, because of reverse polarity, was given to the

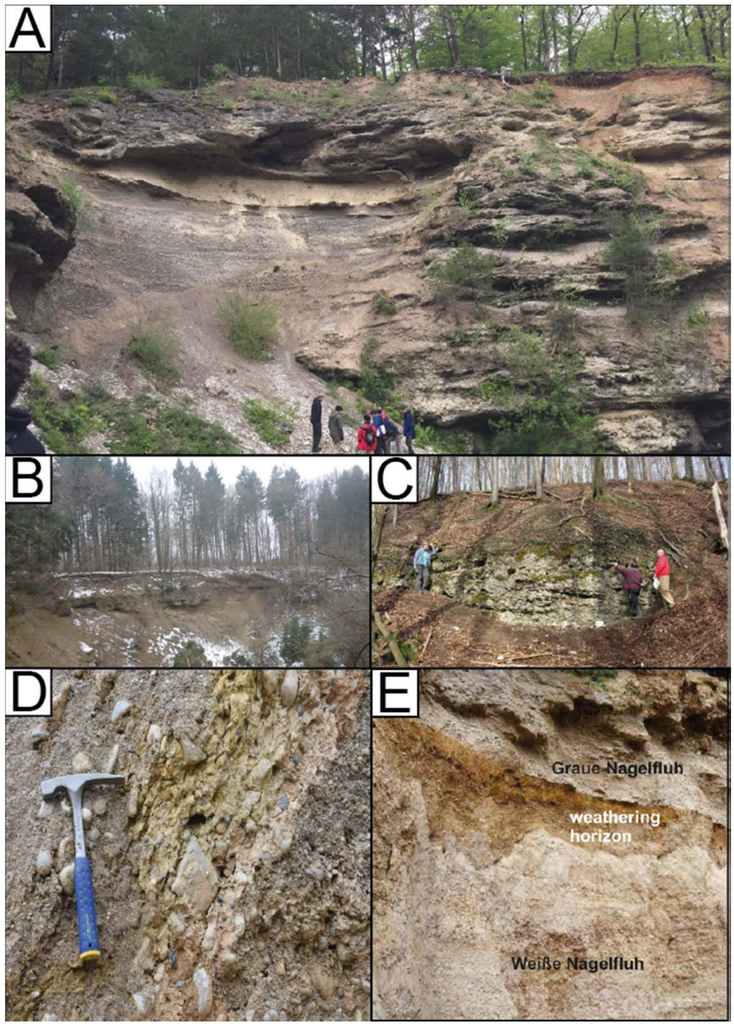

Fig. 3 - A) Outcrop of Deckenschotter at Feusi (Switzerland) (28 in Fig. 1). Weakly cemented, in part cross-bedded, gravels interbedded with a 2-m-thick till layer (beige unit in the center left of photograph). Numerous glacially striated clasts have been found in this till layer. The deposit is capped by deeply weathered till, likely Middle Pleistocene in age (Haldimann et al., 2017). Calculated ^{10}Be-^{26}Al isochron-burial age of the till is 1.3-0.9 Ma (Grischott et al., 2020; Knudsen et al., 2020); B) Outcrop of Deckenschotter at Irchel (Steig Gravels *sensu* Graf, 1996) (28 in Fig. 1). Steig gravels were dated to 0.9 ±0.1 Ma by isochron-burial dating with cosmogenic ^{10}Be and ^{26}Al (Claude et al. 2019; Dieleman et al., 2022); C) Outcrop of Deckenschotter Siglistorf. Calculated ^{10}Be-^{26}Al isochron-burial age of these gravels is1.5 ±0.2 Ma (Akçar et al., 2017) (29 in Fig. 1); D) Close-up view of Bünten till in the Bünten Gravel Pit at Möhlin, Canton of Basel (29 in Fig. 1). This till dates back to 0.5 ±0.1 Ma by isochron-burial dating with cosmogenic ^{10}Be and ^{26}Al (Dieleman et al., 2022). Hammer on the picture is for scale; E) Weathering horizon on top of Weisse Nagelfluh (white conglomerate) overlain by Graue Nagelfluh (grey conglomerate; proglacial deposits of the Günz glaciation) indicating a stable surface under supposed interglacial conditions (location: Kremsmünster, site 19 in Fig. 1, height of the outcrop approximately 4 m).

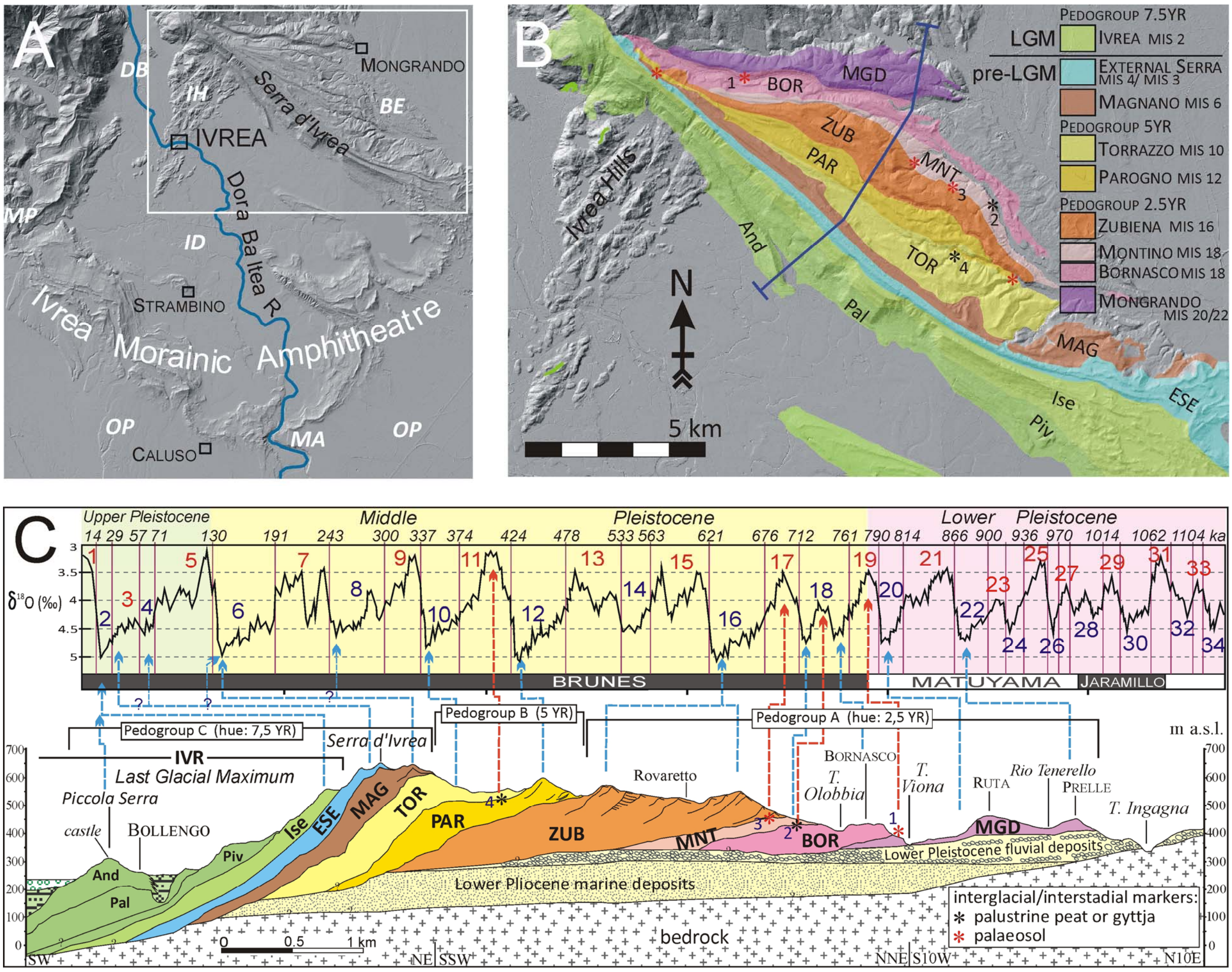

Fig. 4 - A) The 500 km^2 wide Ivrea Morainic Amphitheatre (IMA) (site 2 in Fig. 1) represented by DTM (courtesy of the Piedmont Region) extends to the outlet of the Dora Baltea Valley (DB). The bedrock crops out in the IMA inner sector in the granulite Ivrea Hills (IH) and in the outer western sector in the Monti Pelati peridotite reliefs (MP). The Serra d'Ivrea lateral moraines, 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 mine (BE) extends into a sector previously occupied by the two oldest glacigenic units. White square indicates the location of the geological map showed in B. B) Geological sketch map of the IMA left lateral north-eastern sector, which retains the largest number of recognized glacigenic units in the IMA. The pre-LGM glacigenic succession is divided in seven synthems referred to as many glaciations ranging from the end of Early Pleistocene to the Late Pleistocene. The Bornasco and Montino units separated by an interstadial layer (2) are regarded to as subsynthems. The Ivrea Synthem referred to the LGM is split into Internal Serra (Ise, max LGM advance), Piverone (Piv), Palazzo (Pal) and Andrate (And) subsynthems. C) Geological cross-section of the IMA lateral north-eastern sector (from Gianotti et al., 2015, modified). Profile trace is shown in B (blue line). Interstadial or interglacial markers are indicated with asterisks: 1) Bosa Palaeosol; 2) Sorgente Solfurea peat layer; 3) Comunità palaeosol; 4) Gianetto gyttja layer. The glacigenic sequence is tentatively related to the Pleistocene glaciations. Possible hypotheses are proposed for Magnano and External Serra units. The correlation is made with the global isotopic curve from Lisiecki & Raymo (2005), which is a synthesis of 57 benthic marine oxygen isotope records. Chronological boundaries between marine isotope stages (MIS) are reported.

Langenloiser terrace of the Danube (van Husen & Reitner, 2011a). The Eichwaldschotter glaciofluvial unit in the Salzach piedmont area was tentatively ascribed to MIS 22 (van Husen & Reitner, 2011 a, b), because of the similarity in facies and presence of lithologies of the typical glaciofluvial sediments of the Middle Pleistocene.

According to the evidence from the northern and southern sides, trunk valleys hosted valley glaciers that likely originated from ice domes located in the axial sector of the Alps. In the northern Swiss foreland, the glacial deposits interbedded into the *Deckenschotter* point to an extension of the glaciers similar to but somewhat more extensive than the LGM (cf. Frei, 1912; Graf, 1993; Doppler et al., 2011; Ellwanger et al., 2011; Knudsen et al., 2020).

In the southern side, the first major glaciation has been chronologically constrained by magnetostratigraphy in the Po Plain subsurface and occurred in the late Matuyama chron, between the end of the Jaramillo (0.99 Ma) and the beginning of the Brunhes chron (0.78 Ma; Muttoni et al., 2003, 2007; Scardia et al., 2006, 2012). Based on this chronostratigraphic framework, reverse magnetizations in glacigenic deposits (Carraro et al., 1991; Scardia et al., 2010, 2015; Graf, 2019) have been confidently ascribed to a late Matuyama glaciation and allowed to infer the spatial distribution of the first morainic landforms in the Alpine foreland, even if they have been subsequently eroded. The size of the glaciers and the presence of an Alpine Ice field are still debated. In the distal sector, the Po Plain was filled by outwash streams (Muttoni et al., 2003; Scardia et al., 2006; Garzanti et al., 2011). The Ivrea (San Michele-Borgo and Granero units in Carraro et al., 1991; Mongrando unit in Gianotti et al., 2015) (Fig. 4 and Fig. 5C) and Garda (Ciliverghe Hill and the Chiese River sequence, Fig. 5D) morainic amphitheaters hosted wide glacier piedmont lobes and it is likely that also the Verbano (Morazzone unit, but possibly also the Immacolata and Vivirolo formations) and the Oglio (Valenzano unit) glacier lobes spread out from the valley (Bini, 2004a). With respect to the Adda Glacier, paleomagnetic analysis of the Brugora glaciolacustrine sequence, formerly attributed to the Bozzente unit (Bini et al., 2014), provided reverse magnetization (Fig. 6). Actually, the deposits of the Bozzente unit, as properly defined in terms of weathering profile and geomorphologic position (Zuccoli, 2000; Bini et al., 2014) bear Brunhes chron normal magnetization (Scardia et al., 2010), thus the Brugora site must be ascribed to the late Matuyama glaciations, possibly correlative of the San Salvatore till (Zuccoli, 2000). Remnants of Alpine intermontane basins, such as Ecoteaux, Leffe, and Pianico, also recorded vegetational changes and glacigenic deposits related to the late Matuyama glaciation (Pugin et al., 1993; Muttoni et al., 2007; Scardia & Muttoni, 2009).

According to Häuselmann et al. (2007), intensive glacial overdeepening of Alpine valleys began during the late Matuyama advance (i.e. Aare Valley). Since the late Matuyama, the progressive development of even more extensive glaciations has promoted deep valley incision and overdeepening in many sectors of the Alps. However, it is likely that the late Matuyama ice domes had smaller volumes than in the Middle to Late Pleistocene glaciations, considering even if the extension of the piedmont lobes looks quite similar. It is remarkable that both the French Western Alps and the Eastern Alps are apparently missing remnants of Matuyama glacial units (Ivy-Ochs et al., 2022 and references therein).

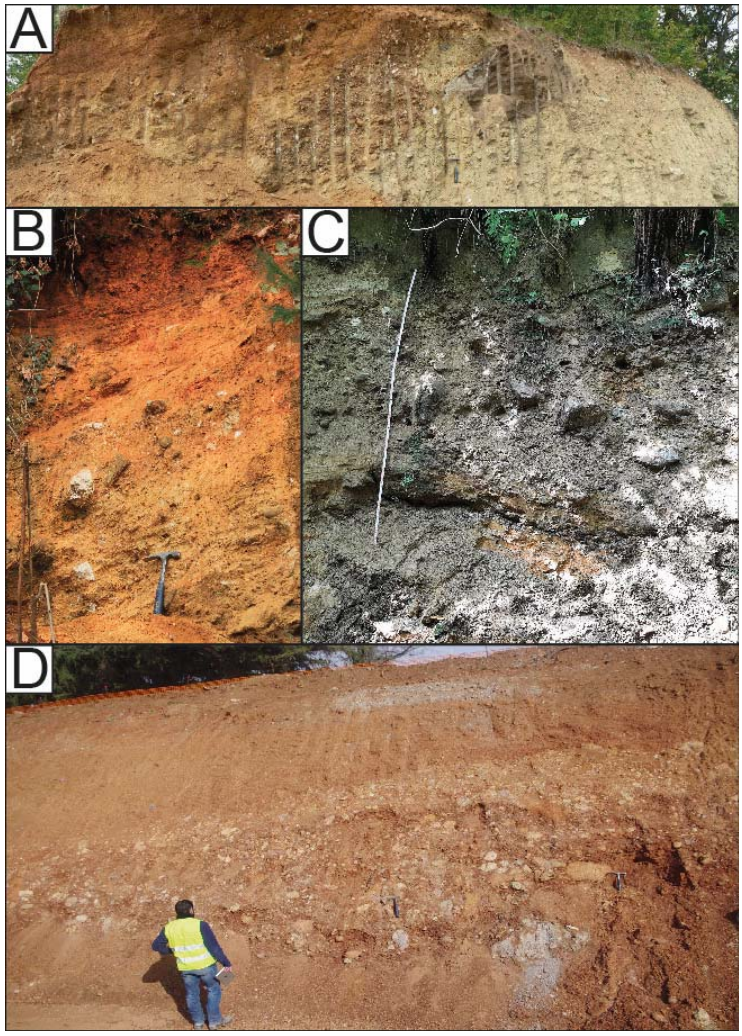

Fig. 5 - A) Frontal moraine of the Bornasco unit (Middle Pleistocene) in the Ivrea end moraine system (site 2 in Fig. 1); B) Weathered lodgment till of the Zubiena unit (Middle Pleistocene) in the Ivrea end moraine system (site 2 in Fig. 1); C) Lodgment till and glaciolacustrine deposits of the Mongrando unit (Early Pleistocene) in the Ivrea end moraine system (site 2 in Fig. 1); D) Weathered fluvioglacial deposits (Middle Pleistocene) of Ciliverghe laying on Early Pleistocene fluvial and glacial units in the Garda end moraine system (site 7 in Fig. 1).

5. EARLY-MIDDLE BRUNHES GLACIATIONS (MIS18-8)

Marine Isotope Stages 16 and 12 are related to the greatest extents reached by boreal ice sheets (Batchelor et al., 2019) as recorded by the prominent spikes of $\delta^{18}O$ (Lisiecki & Raymo, 2005, Bell et al., 2014; Farmer et al., 2019). It is likely that also in the Alps these cold phases produced the spread of the glaciers. Considering the size of the Laurentide Ice Sheet (LIS) and the European Ice Sheet (EIS), a circulation model similar to the one that produced the Alpine LGM (Florineth & Schlüchter, 2000; Luetscher et al., 2015; Monegato et al., 2017) can be supposed. However, the narrative of this period (761-242 ka BP, between MIS 18 and MIS 8 cold stages) strongly suffers from lack of chronologic constraints, and glacial units are best grouped as pre-LGM deposits with normal magnetic polarity.

In the Swiss sector, in addition to field evidence, paleobotanical data and luminescence dating were the basis for distinguishing three major glacial units: Möhlin, Habsburg and Hagenholz glaciations (Preusser et al., 2011; Schlüchter et al., 2020). Several detailed studies on boreholes led to the conclusion that the Middle Pleis-

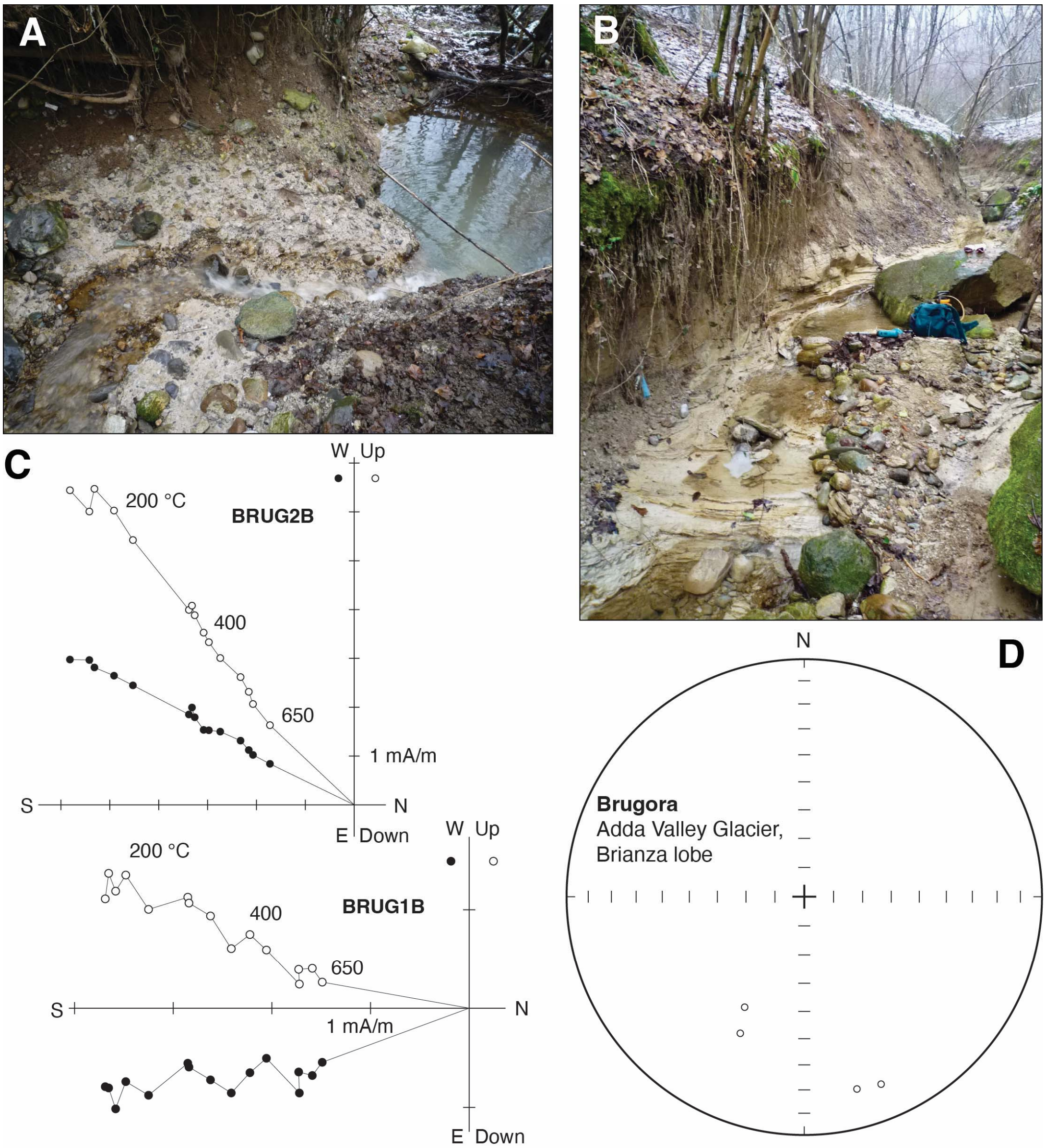

Fig. 6 - The Brugora site from the Brianza lobe of Adda Glacier (site 5 in Fig. 1). A) lodgement till passing upward to B) glaciolacutrine fine-grained, laminated deposits with drop-stones. C) Orthogonal projection of thermal demagnetization data of representative samples from the Brugora site. D) Equal-area projection of the characteristic component vectors determined for the Brugora glaciolacustrine deposits. Open circles indicate negative inclinations and plot onto the upper hemisphere.

tocene was a period of intense incision and valley overdeepening after deposition of the Deckenschotter units. In many foreland valleys of the Swiss sector the bedrock floor is hundreds of meters beneath the present surface topography (Jordan, 2010; Preusser et al., 2010). Palynological and luminescence data suggest that aggradation phases and filling of the overdeepened valleys began no later than 450 ka (MIS 12; Preusser et al., 2010; Reitner et al., 2010; Gegg et al., 2023; Schwenk et al., 2022), possibly related to erosion-driven flexural uplift of the Alps (Scardia et al., 2012). Recent studies ascribed the overdeepening in the Bern area/Aare Valley to MIS 12 (Gegg et al., 2020; Schwenk et al., 2022). Recently, Dieleman et al. (2022) studied the till layer (Fig. 3D), which is exposed in a gravel pit at Möhlin (Canton of Basel) and attributed it to the Möhlin glaciation. The cosmogenic nuclide analysis in the clasts embedded in this till layer indicated a deposition age of 0.5 ±0.1 Ma.

In the Austrian foreland, paleomagnetic constraints in loess successions (Scholger & Terhorst, 2013) and geological considerations (van Husen & Reitner, 2011a, b) were used to tentatively correlate the Günz and Mindel glaciations with the severe global climatic deteriorations of MIS 16 and MIS 12. In the Austrian part, the preserved morphological and sedimentary record indicates the Mindel glaciation as the largest one. Günz end moraines are only preserved where the Mindel glaciers had a slightly different advance direction. An outstanding Middle Pleistocene succession at Kremsmünster in the Krems Valley (19 in Fig. 1) is ascribed to glaciofluvial aggradation (Kohl, 2000); it is stratigraphically confined between Günz and Mindel tills and glaciofluvial deposits, suggesting a cold phase of minor landscape modification between MIS 16 and MIS 12. This stratigraphic architecture still needs chronological constraints for a better assessment.

In many morainic amphitheaters of the southern Alpine sector the early-middle Brunhes glaciations are distinguished in the stratigraphic architecture by the means of bounding surfaces marked by buried soils (paleosols), pedostratigraphy based on surface soils (Bini et al., 2004a; Gianotti et al., 2015; Fioraso et al., 2021), occurrence of loess (Venzo, 1965) or interbedded organic layers containing warm flora (Pini et al., 2009; Gianotti et al., 2008; 2015). In detail, in the eastern sector of the Ivrea Morainic Amphitheatre, seven units (Bornasco, Montino, Zubiena, Parogno, Torrazzo, Magnano and External Serra) are tentatively ascribed to the Middle Pleistocene glaciations (Fig. 4), apart from the possibility of a Late Pleistocene, pre-LGM age for the External Serra unit (Gianotti et al., 2008; 2015). The Mongrando (MIS 22-20, with reversed polarity) and Bornasco (MIS 18) units are separated by the Bosa paleosol (MIS 19 interglacial). The Bornasco (MIS 18e) (Fig. 5A) and Montino (MIS 18a) sub-units are separated by the Sorgente Sulfurea peaty layer with cool-climate pollens (MIS18b-d interstadial) and so they can be correlated to the two peaks of the MIS 18 glaciation, Montino sub-unit (MIS 18) and Zubiena unit (MIS 16) (Fig. 5B) by the Cascina Comunità palaeosol (MIS 17 interglacial), the Parogno (MIS 12) and Torrazzo units (MIS 10) by the Cascina Gianetto palustrine gyttja with warm-climate pollens (MIS 11.3 interglacial, Gianotti et al., 2015). Other stratigraphic boundaries (Zubiena-Parogno and Torrazzo-Magnano) were identified by pedostratigraphy; pedogroup A (Mongrando to Zubiena units) shows hue 2.5YR, pedogroup B (Parogno and Torrazzo units) hue 5YR, and pedogroup C (Magnano, External Serra and Ivrea synthems) hue 7.5YR. Within the less ancient pedogroup, the Magnano unit (MIS 8 or, more likely, MIS 6) is distinguishable from the External Serra unit (MIS 6, MIS 4 or MIS 3, based on pre-LGM exposure ages of erratic boulders) by soils with a thicker B horizon (> 2 m) and a higher degree of weathering of the clasts.

In others morainic amphitheaters of the Lombardy piedmont plain several Middle Pleistocene landform remnants (moraines and kame terraces) were distinguished through the occurrence of paleosols, loess cover and peat layers (Bini et al., 2004a, 2014). Each moraine system has its own stratigraphic subdivision (Tab. 1), even if geochronological constraints are poor. In the Verbano area thick aeolian deposition ascribed to Middle Pleistocene cold phases have been distinguished by means of paleosols (Terhorst & Ottner, 2003; Terhorst et al., 2012; Terhorst, 2013). At east of the Garda system, glacial deposits related to early-middle Brunhes are lacking or debated (Zanferrari et al., 2013). The same lack of information occurs in the French side of the Western Alps, where glaciofluvial units were detected outside the "external moraine complex" and ascribed to cold phases of the Middle Pleistocene (Mandier, 1982).

6. THE PENULTIMATE GLACIATION (MIS6)

The penultimate glaciation occurred at the end of the Middle Pleistocene and it is considered as the largest in term of ice sheets volume (Batchelor et al., 2019). Deposits related to this cold phase in the Alps were dated with luminescence methods on glaciofluvial and glaciolacustrine exposed successions (Preusser & Schlüchter, 2004; Bickel et al., 2015a, b; Salcher et al., 2015; Schielein et al., 2015; Rades et al., 2018). In the Swiss-German sector, detailed sedimentological work and luminescence dating have been done also on cores taken from the overdeepened valleys (Dehnert et al., 2012; Lowick et al., 2015; Buechi et al., 2018), obtaining ages from MIS 6 or even somewhat earlier (Gegg et al., 2022). These studies depicted several phases of glacier advance and withdrawal, suggesting complex dynamics of the Rhine glacier system from the end of MIS 7 to the waning stages of MIS 6. In many end-moraine systems of the Alps, glacial deposits and landforms related to the penultimate glacial cycle are often close to those of the LGM, suggesting a comparable extension. They are distinguishable because their soils are much more developed, disallowing their attribution to the later Pleistocene (e.g., Venzo, 1977; Castiglioni, 2004; Zanferrari et al., 2008; Buoncristiani & Campy, 2011; Doppler et al., 2011; Preusser et al., 2011; Ellwanger et al., 2011; van Husen & Reitner, 2011a; Gianotti et al., 2015; Fioraso et al., 2021). In the French Western Alps it is considered the "external moraine complex", tentatively associated to the Riss (Buoncristiani & Campy, 2011). In the eastern part of the Austrian Alps an exceptionally large MIS 6 glaciation with terminal moraines up to 40 km downvalley of their LGM counterparts, like in the Enns Valley (Eastern Alps), did occur (Fig. 7). Such findings in narrow and gently sloping valleys can be explained by ice-dynamical reasons, such as ice congestions resulting in a disproportionate increase of accumulation areas of the Salzach and Enns (van Husen, 2000), promoted by the moderate additional lowering of the ELA of around 100 m (Penck & Brückner, 1901-1909). In the Julian Alps, ice-marginal and glacial deposits were dated to MIS 6 glaciation in the Soča Valley (Bavec et al., 2004; Jamšek Rupnik et al., 2022). In the southern side of the Alps, MIS 6 moraines are normally very close or partially buried by LGM terminal moraines. This situation can be detected in many morainic amphitheaters (Cremaschi, 1987; Rossato et al., 2013; Gianotti et al., 2015; Fioraso et al., 2021; Kamleitner et al., 2022). In the Verbano and Lario amphitheatres, the Besnate Allogroup, formerly ascribed to the Middle-Late Pleistocene (Bini, 1997), has been dated to the LGM (Kamleitner et al., 2022), suggesting that Golasecca and Binago units (Tab.1) can be tentatively ascribed to MIS 6. In the Tagliamento sector the MIS 6 moraines and glaciofluvial units were traced from the end moraine system to the coastline (Zanferrari et al., 2008; Pini et al., 2009; Fontana et al., 2010).

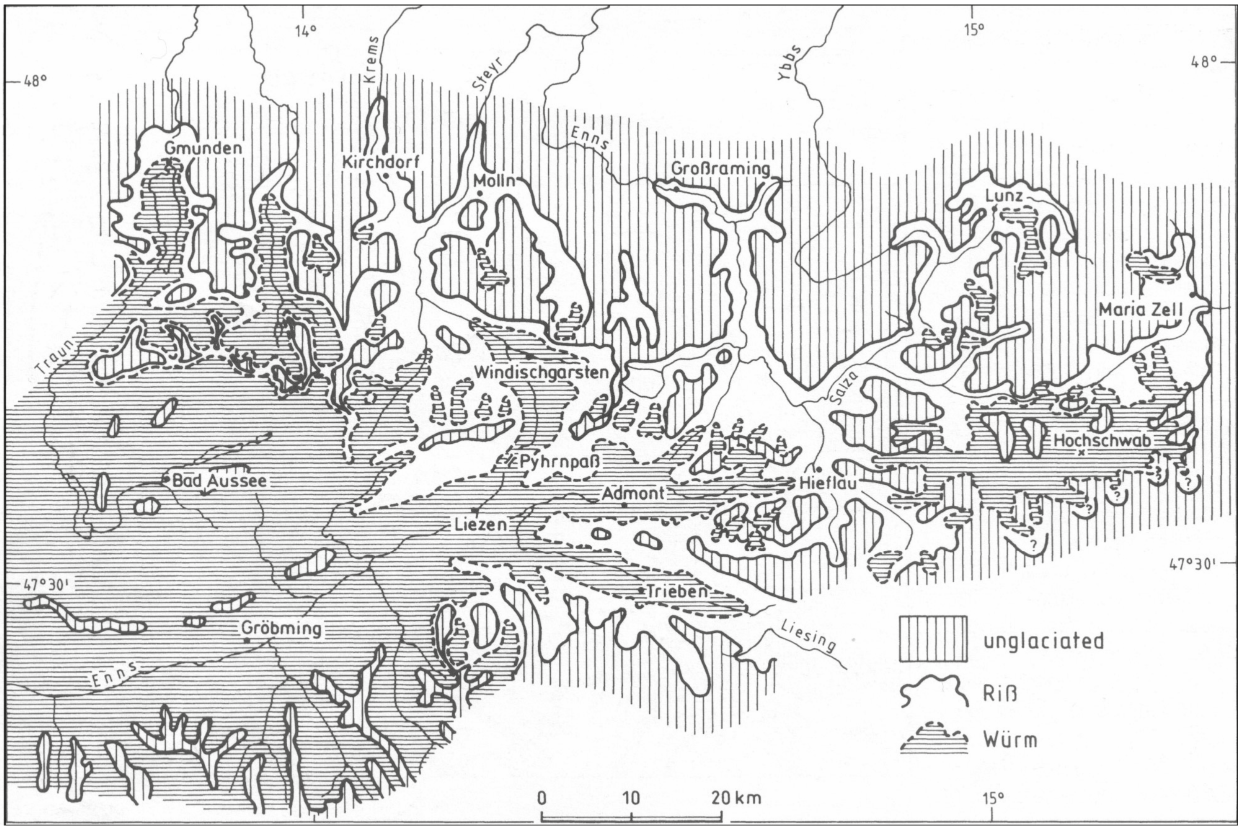

Fig. 7 - Glacier extent during the Würmian (MIS 2) and Rissian (MIS 6) in the Enns valley and environs and in the Steyr and Ybbs valleys (mod. after van Husen, 2011a).

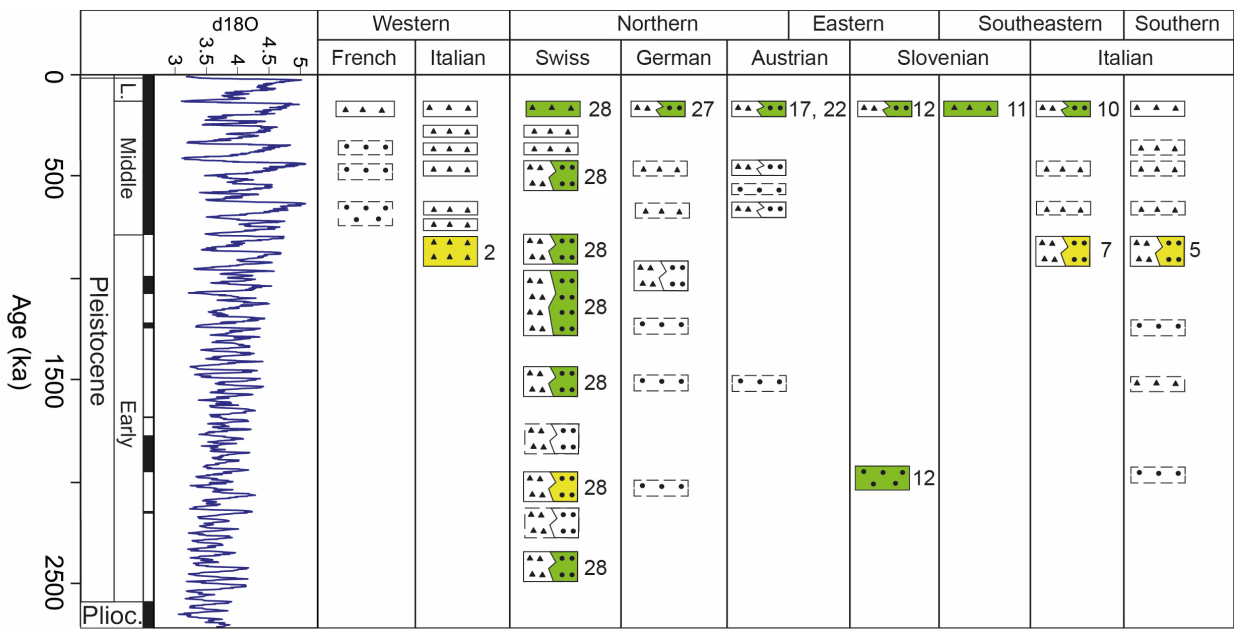

Fig. 8 - Correlation sketch of the glacial/glaciofluvial units recognized for each sector of the Alps; numbers indicate the sites of Fig. 1 and Tab. 1. Black triangles indicate glacial unit and black dots glaciofluvial unit. Green color points to available chronology; yellow color points to available reverse polarity. $\delta^{18}O$ curve from Lisiecki & Raymo (2005).

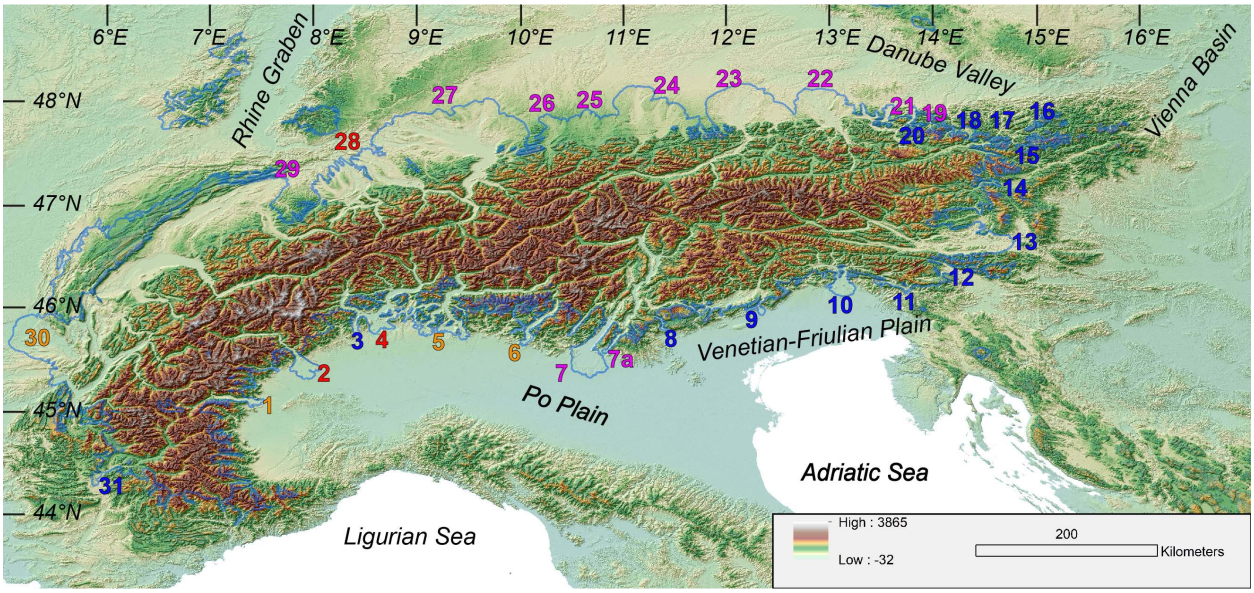

Fig. 9 - Map of the Alps with the sectors of Tab. 1 colored for number of recorded glaciation: blue (1-2), purple (3-4), orange (5-6), red (>6).

7. DISCUSSION

7.1. How many glaciations?

Located at mid latitude between the Mediterranean Sea and continental Europe, the Alps are the highest mountain range of this continent and are very sensitive to climate changes. In this way, they can have hosted mountain glaciers since the onset of the Pleistocene glaciations. The available data of glacigenic deposits older than the Late Pleistocene are numerous, also thanks to more than 150 years of research, and can provide insights on how the Pleistocene cold stages affected the Alps and how many times.

According to the available data from the area with the more detailed stratigraphic successions (Fig. 8), a minimum of 13 different glacier advances of Early to Middle Pleistocene age are recognized in the Swiss Foreland (Preusser et al., 2011; Schlüchter et al., 2020), about nine to ten in the Ivrea and Verbano sectors (Bini, 1997; Gianotti et al., 2015; Zuccoli, 2000), but apparently only four in the Lake Garda area (Cremaschi, 1987) and two in the Tagliamento system (Zanferrari et al., 2013). These events should represent locally just the major glacier expansions onto the foreland (Fig. 9) and other cold stages (e.g. MIS 14 and MIS 8 stages, according to their weaker isotopic signal in the MIS curve) should have seen glaciers expanded but remaining within the Alpine valleys. Moreover, the occurrence of multiple phases of glacier advance and withdrawal within the same cold stage (i.e., Dehnert et al., 2012; Lowick et al., 2015) has to be carefully considered for a correct counting of glaciation in a single sector.

Glaciofluvial input in the foreland is also an important tracer of sediment production and delivery during cold stages (Scardia et al., 2006, 2012; Garzanti et al., 2011; Preusser et al., 2021; Marcolla et al., 2021). However, to distinguish them in the Lower-Middle Pleistocene successions implies the coupling of the sedimentary analyses with paleoclimatic proxies (i.e. pollen data) that indicate which part of the succession can be related to cold stages. For Early Pleistocene glaciations this means multidisciplinary investigation on deep cores of the depocenter areas (i.e., Po Plain, Rhine graben, and Vienna Basin) coupled with investigation in major valleys (Anselmetti et al., 2022).

7.2. Extent of glaciations?

As depicted by the distribution of the preserved record, we can argue how glacier expansions developed during each cold stage. The reconstruction of the paleoclimate during the LGM showed how the Alps are sensitive to small shifts in atmospheric that conditioned the ELA lowering circulation (Luetscher et al., 2015; Monegato et al., 2017; Gribenski et al., 2021). Moreover, the asymmetry of the Alpine range in terms of distribution of high elevation areas would contribute to differentiate the major accumulation sectors according to their location with respect to the storm tracks feeding the glaciers. As remarked, for example, by the large extent of the MIS 6 glaciation in the Austrian sector (Ybbs and Enns in Tab. 1 and Fig. 7), we suppose that slightly lower ELA can cause the development of a much larger glacier system. In this perspective, the concept of a most extensive glaciation can be applied only in specific sectors of the range and must not encompass the whole Alps. The fact that MIS 12, MIS 6 or LGM frontal moraines occupy the outermost position in eastern and southeastern Alps more frequently than in the southwestern or the northern Alps points to different distribution of precipitation during each cold phase, determining the size of the glaciers and piedmont lobes.

7.3. Which were the major glaciations?

Dissimilar distribution of the glacial units in the circumalpine area points to a reduced number of “major” glaciations and the most extensive glaciation concept

Tab. 1A

	Glaciated basin	Unit	Age			Key references
			Attribution	Dates	Other constraints	
1	Susa Valley (Rivoli/Avigliana)	Cresta Grande	MIS 6	-	thick palaeosol on top (10-7.5YR hue color index), stratigraphic correlation	Fioraso et al., 2021
		Truc Carlevè	Middle Pleistocene	-	thick palaeosol on top (5YR hue color index)	
		Truc Monsagnasco	Middle Pleistocene	-	thick palaeosol on top (7.5-5YR hue color index)	
		Truc Bandiera	Middle Pleistocene	-	thick palaeosol on top (5YR hue color index)	
		Sangano	Early?-Middle Pleistocene	-		
2	Aosta Valley (Ivrea)	External Serra	MIS 6 (MIS 4 or MIS 3)	Cosmogenic ages ^{10}Be: 35.0 ±3.9 and 30.8±3.5 ka	pedostratigraphy	Gianotti et al., 2008, 2015
		Magnano	MIS 8	-	pedostratigraphy (7.5YR hue color index), stratigraphic correlation	
		Torrazzo	MIS 10		pedostratigraphy (5YR hue color index) pollen data from a basal palustrine layer (MIS 11 interglacial	
		Parogno	MIS 12		pollen data from a basal peat layer, 5YR hue color index	
		Zubiena	MIS 16		paleosol (2.5YR hue color index), stratigraphic correlation	
		Montino/Bornasco	MIS 18?		pollen data from a peat layer	
		Mongrando	MIS 20-22		reverse polarity, palaeosol, pedostratigraphy (10 R-2.5YR hue color index)	Carraro et al., 1991; Gianotti et al., 2015
3	Ossola Valley (Orta)	Soriso	Middle Pleistocene		normal polarity	Piana et al., 2017
		Gargallo	Middle Pleistocene		thick palaeosol on top	
4	Ossola and Ticino valleys (Verbano)	Golasecca	Middle Pleistocene		paleosol (10-7.5YR hue color index), stratigraphic correlation	Zuccoli, 2000; Bini et al., 2014
		Albizzate	Middle Pleistocene		paleosol (7.5YR hue color index), stratigraphic correlation	
		Morazzone Group (3 units)	Early Pleistocene?		paleosol (5-7.5YR hue color index), stratigraphic correlation	
		Castronno	Early Pleistocene?		thick palaeosol on top and stratigraphic correlation	
		Immacolata	Early Pleistocene?		stratigraphic correlation	
		Vivirolo	Early Pleistocene?		stratigraphic correlation	
5	Adda Valley (Lario and Mendrisio)	Binago	Middle Pleistocene		paleosol (10-7.5YR hue color index), stratigraphic correlation	Zuccoli, 2000; Bini et al., 2014
		Specola	Middle Pleistocene		paleosol (5-7.5YR hue color index), stratigraphic correlation	
		Bozzente Group (2 units)	Middle Pleistocene		paleosol (10-2.5YR hue color index), stratigraphic correlation	Cremaschi et al., 1985; Zuccoli, 2000
		San Salvatore	MIS20-22		reverse polarity	Scardia et al., 2010
		Casanova Lanza Group	Early Pleistocene?		stratigraphic correlation	Bini et al., 2014
6	Camonica Valley (Sebino)	Monterotondo	Middle Pleistocene		paleosol (10-7.5YR hue color index), stratigraphic correlation	Cassinis et al., 2011
		Monte Piane	Middle Pleistocene		paleosol (5-7.5YR hue color index), stratigraphic correlation	
		Fantecolo	Middle Pleistocene		paleosol (5-7.5YR hue color index), stratigraphic correlation	
		Camignone	Middle Pleistocene		paleosol (10-5YR hue color index), stratigraphic correlation	
		Paderno di Franciacorta	Middle Pleistocene		paleosol (10-5YR hue color index), stratigraphic correlation	
		Valenzano	Early Pleistocene?		paleosol (10-2.5YR hue color index), scattered boulders	
7	Adige/Sarca valleys (Garda)	Sedena/Albare	Middle Pleistocene		thick palaeosol on top and stratigraphic correlation	Cremaschi, 1987, Accorsi et al., 1990
		Carpenedolo	Middle Pleistocene			
		Carpenedolo-Montichiari	Middle Pleistocene			
		Ciliverghe	MIS20-22		reverse polarity	Cremaschi, 1987; Baroni & Cremaschi, 1987; Scardia et al., 2015
7a	Adige Valley (Rivoli Veronese)	Monte Crivellino	Middle Pleistocene			Accorsi et al., 1990
		Caprino	Middle Pleistocene			
		Pesina	Early Pleistocene?			
8	Astico Valley (Cogollo)	Seghetta	MIS 6		pollen data	Rossato et al., 2013
		Prà de Ochi	Middle Pleistocene			Cucato, 2001
9	Piave Valley	Riss glacial	Middle Pleistocene		thick palaeosol on top and stratigraphic correlation	Venzo, 1977
10	Tagliamento	Plaino	MIS 6		Pollen data and stratigraphic correlation	Zanferrari et al., 2008; Lowick et al., 2010
		Ledrania	Middle Pleistocene		weathered glacial remnants only in the lower valley	Monegato and Stefani, 2011; Zanferrari et al., 2013
11	Soča/Isonzo	Ravni Laz/ Modrejce	MIS 6	IRSL dates in Bovec: 154.7 ±22.8 ka and U/Th dates: 152.7 ka. OSL dates in Modrejce: 165 ±65 ka and 169 ±21 ka		Bavec et al., 2004; Bavec & Verbic, 2011 Jamšek Rupnik et al., 2022
12	Sava	Bled-Radovljica	MIS 6	IRSL dates: 156 ±18 ka		Bavec & Verbic, 2011
		Udin Boršt	Early Plestocene	Cosmogenic age: 1.9 ±0.2 Ma		Mihevc et al., 2015
13	Drau	Riss glacial	MIS 6			Bobek, 1959; van Husen, 1989

Tab. 1B

	Glaciated basin	Unit	Age: Attribution	Age: Dates	Age: Other constraints	Key references
14	Mur	Riss glacial	MIS 6			Spreitzer, 1961
15	Erlauf	Riss glacial	MIS 6			Moser & Schnabel, 2019
16	Laming	Riss glacial	MIS 6			Bryda et al. 2013
17	Ybbs	Riss glacial	MIS 6	Luminescence dates: 150±14 ka (pIRIR225) to 129±14 ka (OSL)		Nagl, 1970; Bickel et al. 2015a
18	Enns	Riss glacial	MIS 6			Egger & van Husen, 2011
19	Steyr-Krems	Riss glacial	MIS 6			van Husen, 1975, 2000; Kohl, 1999
		Mindel glacial	MIS 12			Kohl, 2000 van Husen, 2000;
		Günz glacial	MIS 16			
20	Alm	Riss glacial	MIS 6			Egger, 2007a
21	Traun	Riss glacial	MIS 6		pollen data	Egger, 2007a, b; van Husen & Egger, 2014
		Mindel glacial	MIS 12			
		Günz glacial	MIS 16			Kohl 2000; Egger, 2007a
22	Salzach	Riss glacial	MIS 6	OSL dates: 193±30 ka 188±27 ka		Weinberger, 1955; Rupp et al., 2011 Salcher et al., 2015
		Mindel glacial	MIS 12			Weinberger, 1955; van Husen, 2000; Doppler et al., 2011
		Günz glacial	MIS 16			
23	Inn-Chiemsee	Riss glacial	MIS 6			Doppler et al., 2011
		Mindel glacial	MIS 12			
24	Isar-Loisach	Riss glacial	MIS 6			Doppler et al., 2011
		Parsberg SW Puchheim	Middle Pleistocene			
25	Lech-Wertach	Lengenfeld-Ludwigsberg	MIS 6			Doppler et al., 2011
26	Iller	Riss glacial	MIS 6			Doppler et al., 2011
		Holzheuer Höhe Brandholz-Manneberg	Middle Pleistocene			
27	Rhein	Doppelwall Riss	MIS 6	IRSL dates: 149 ±15 to 179 ±17 ka		Rades et al., 2018
		Laupertshausen	Middle Pleistocene			Schreiner, 1997; Doppler et al., 2011
		Heiligenberg	Early?-Middle Pleistocene			
		Schienerberg Deckenschotter	Early Pleistocene			Graf, 2009a
		Chroobach Deckenschotter	Early Pleistocene	Cosmogenic age: 1.8 ±0.1 Ma		Graf, 2009a; Dieleman et al., 2022
28	Reuss/Linth-Rhein/Rhein	Beringen glaciation	MIS 6	IRSL dates (~185 ka) at Klettgau OSL dates from 159±8 ka to 205±12 at Rinikerfeld		Graf, 2009b; Keller & Krayss, 2011, Preusser et al., 2011; Dehnert et al., 2010, 2012; Lowick et al., 2015; Buechi et al., 2017; Schlüchter et al., 2020; Dieleman et al., 2022; Gegg et al., 2022
		Hagenholz glaciation	Middle Pleistocene			
		Habsburg glaciation	Middle Pleistocene			
		Möhlin glaciation	Middle Pleistocene	Cosmogenic age: 0.5 ±0.1 Ma		
	Rhein/ Linth-Rhein	Irchel Deckenschotter	Early Pleistocene	Cosmogenic ages: 2.6 - 0.9 Ma		Claude et al., 2019; Knudsen et al., 2020; Dieleman et al., 2022a
				mammal fossils: 2.6 - 1.8 Ma (MN 17)		Bolliger et al., 1996
	Reuss/ Linth-Rhein	Iberig Deckenschotter	Early Pleistocene	Cosmogenic age: 1.3 - 0.7 Ma		Grischott et al., 2020; Knudsen et al., 2020
		Tromsberg Deckenschotter	Early Pleistocene	Cosmogenic age: 1.3 - 0.9 Ma		
		Feusi Deckenschotter	Early Pleistocene	Cosmogenic age: 1.3 - 0.9 Ma		
		Siglistorf Deckenschotter	Early Pleistocene	Cosmogenic age: 1.5 ±0.2 Ma		Akçar et al., 2017
		Uetliberg/Albis Deckenschotter	Early Pleistocene		reversed polarity	Graf, 2019
		Stadlerberg Deckenschotter	Early Pleistocene	Cosmogenic age: $2.4^{+2.3}_{-1.2}$ Ma		Claude et al., 2017; 2019
29	Aare	Thalgut	Middle Pleistocene			Schlüchter, 1989; Preusser & Schlüchter, 2004
	Rhone-Valais	Jura Mountains, scattered Alpine boulders	Middle Pleistocene	Cosmogenic ages: >150 ka		Graf et al., 2015
		Meikirch	Middle Pleistocene, MIS 8			Schlüchter, 1989; Preusser et al., 2005
30	Isere-Rhone	Barolles	Middle Pleistocene			Mandier, 1982
		Ozon	Middle Pleistocene			
		Ternay	Middle Pleistocene			
		Louze-Montailloud	Middle Pleistocene			
31	Durance	Sisteron (Riss)	Middle Pleistocene			Gabert, 1984

Tab. 1 (A and B) - Framework of Early-Middle Pleistocene stratigraphic units in the Alps related to glaciations. The regions are labeled and referred to Fig. 1 for location.

should be applied with local significance, not being suitable for the whole Alpine range. As the LGM can be considered a major one, the paleoclimatic setting that produced such an ice extent can be assumed also for the other large glacier extents in the Alps. Nevertheless, favorable microclimate conditions can promote local glacier advances in periods not necessarily in tune with the cold stages (Gribenski et al., 2021). Considering the Ivrea-Verbano area, available data show that six glacier advances took place in the Middle Pleistocene (Bini, 2012; Gianotti et al., 2015, Tab. 1) as related to the stratigraphy of the foreland (Scardia et al., 2012; Garzanti et al., 2011), almost every cold stage could have here a preserved sedimentary signature. This can be related to the high elevation accumulation area (and in addition, located very close to the piedmont area in the case of the Ivrea Amphitheatre), which is able to host a large valley glacier and a powerful piedmont lobe when climate became cold enough to force a lowering of the ELA. On the northern side, the other major ice domes (Rhine and Engadine; Florineth & Schlüchter, 2000; Kelly et al., 2004) promoted four major glacier advances in the Swiss foreland during the Middle Pleistocene (Preusser et al., 2011); in this framework, the Beringen glaciation was dated to MIS 6 (Lowick et al., 2015; Buechi et al., 2017) and the Möhlin glaciation to MIS 12 (Gaar & Preusser, 2017; Preusser et al., 2021; Dieleman et al., 2022). These sectors have high accumulation areas fed both by westerly and southerly circulation and can develop large glaciers in both configurations.

On the other side, in the northeastern Alps the larger extent is related to the Riss with overflow of Enns glacier into weakly glaciated catchments (van Husen, 2000); this phase is ascribed to MIS 6 (van Husen, 2000; van Husen & Reitner, 2011a). Same processes are likely for the Mindel (MIS 12) glaciation, where preserved moraines and related glacigenic deposits in Austria and southeastern Bavaria are even more distal from the Alpine front. In the southeastern side (Piave, Tagliamento and Soča catchments), all the morainic amphitheaters show MIS 6 deposits slightly outside the LGM (Venzo, 1977; Monegato et al., 2010; Rossato et al., 2013). No more external glacial deposits have been observed, thus indicating that MIS 6 bore the largest configuration in the sector.

The longitudinal extremes (French side and eastern Austrian sector) show only one Middle Pleistocene glacial unit (Tab. 1 and Fig. 9) larger than LGM. Considering that in the Western Alps glacier growth is favored by westerly circulation, while the Eastern Alps are dominantly fed by southerly storm tracks, these units can testify to different cold stages of the Middle Pleistocene.

The Garda and Adda systems, which are fed by the largest mountain catchments of the southern side of the Alps, show three major units in the Middle Pleistocene, besides the LGM and the late Matuyama (Cremaschi, 1987; Bini, 2012). Considering their size, these systems need mostly southerly circulation for the expansion of the glacier network and formation of a piedmont lobe. In this perspective, apparently only three times in the Middle Pleistocene was the circulation comparable to the LGM, possibly in phase with the large extents of the boreal ice sheets (Batchelor et al., 2019) and especially to the Laurentide Ice Sheet, whose topography forced the polar front to the mid latitudes and the storm track into the Mediterranean (Beghin et al., 2015; Del Gobbo et al., 2022).

8. CONCLUSIONS

The nearly 200 years of research on Alpine glaciations has shown that the Alps hosted extensive glaciations in correspondence of several Pleistocene cold stages and likely smaller valley glaciers during the minor climate deteriorations. Thanks to the stratigraphic and geochronological data accumulated in the last decades, new insights have been provided for depicting the Early Pleistocene glaciations, whose extent was previously hypothetical, but now, especially in the northern foreland, their record is continuously updated.

The onset of glaciations since the late Matuyama (MIS 22-20) is better recognized in many end moraine systems in the southern side of the Alps and correlating with foreland core stratigraphy. The updated chronology of the Middle Pleistocene phases indicates it is likely that every sector has had its own most extensive glaciation in a different time span. The dissimilar architecture of the glacigenic units at the outlet of the major Alpine catchments points to a different behavior of the glaciers depending on global paleoclimate configuration, which was likely dissimilar from one stage to the other. Moreover, in the large accumulation areas of the Central Alps (Adige, Adda and Inn) the development of an extensive interconnected glacier network with associated piedmont lobes required abundant snow supply also from the southerly circulation, which was promoted by the large extent of the Laurentide Ice Sheet. In the higher accumulation areas (Valais, Dora Baltea, Rhine-Reuss and Ticino-Toce) a larger number of glacial units was recorded probably because a small ELA lowering in these catchments could lead to glacier advance.

Finally, the Alps remain the most studied mountain range for reconstructing extents of Quaternary glaciers and testing new methods and models. The long lasting studies are a treasure to preserve and a motivation for even better depicting the climatic and geomorphological evolution of the highest mountain environment of central Europe.

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