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LAST GLACIAL MAXIMUM GLACIOLACUSTRINE DEPOSITS FROM THE ADIGE MORAINE AMPHITHEATRE (RIVOLI VERONESE, NORTHERN ITALY): DISTRIBUTION, SEDIMENTARY FACIES, AND SIGNIFICANCE

Andrea Pezzotta [1], Guido S. Mariani [2], Mattia Marini [1], Mauro Cremaschi [1], Andrea Zerboni [1]

Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, Milano, Italy.
Dipartimento di Scienze della Terra, Università degli studi di Torino, Torino, Italy.

Corresponding author: Andrea Pezzotta <andrea.pezzotta@unimi.it>

ABSTRACT: Proglacial lakes formed between ridges, small fluvioglacial plains and glacier fronts of end-moraine systems are excellent sedimentary archives capable of accurately recording environmental variations linked to deglaciation. The Adige Moraine Amphitheatre (AMA) at the outlet of the Adige Valley in the southern foothill of the Alps (Rivoli Veronese, Verona; Northern Italy) is a multi-moraine ridges system built during the Last Glacial Maximum (LGM) by two subsequent glacial advances of the Adige Glacier. Within the innermost moraine arc of the AMA, the topography of glacial deposits acted as a dam originating two separated proglacial lakes, collecting meltwaters. Geomorphological and geological mapping allowed identifying the vestiges of a complex glaciolacustrine system with a branching proglacial lake in which deltaic and ice-contact situations coexisted. Four sedimentary facies associations suggestive of ablating ice-front, glaciofluvial, deltaic, and glaciolacustrine depositional settings were recognised, and their spatial relationship clarified through facies analysis. Results suggest the proglacial lake was likely enclosed by the glacier front, moraine ridges, and other glacial deposits that obstructed the pre-existent Adige Canyon, and that the two identified lake branches coalesced during the final phase of glacier retreat. The process controlling the draining of the lake is not completely known, but the occurrence of boulders (recurrently named as "erratics") in the uppermost deposits of the Adige River glaciofluvial fan to the south of AMA suggests these may represent mega-clasts transported during the post-LGM collapse of the Adige Glacier. We propose that these mega-clasts were mobilized by a glacial lake outburst flood resulting from the collapse of the deposits obstructing the Adige Canyon upstream. Our results add to better understanding of the AMA deglaciation phases and to the reconstruction of the LGM-Post-Glacial transition period in the foothills of the southern Central Alpine region.

Keywords: Proglacial lake, Adige Moraine Amphitheatre, Last Glacial Maximum, deglaciation, moraine amphitheatre.

1. INTRODUCTION

Understanding sedimentary processes of moraine systems is key to reconstruct past glacial dynamics. Most of the best-studied moraine amphitheatres (also referred to as glacial amphitheatres) are relatively large examples formed after long sequences of glacial oscillations (Ehlers & Gibbard, 2004; Ivy-Ochs et al., 2018). Moraine (or glacial) amphitheatres correspond to semi-circular, concentric end-moraine systems, built up during the Middle and Upper Pleistocene by glacier piedmont lobes flowing out of the major Alpine valleys (Fig. 1a; Fairbrigde, 1968; Cremaschi, 1987; Bini & Zuccoli, 2004). Despite large glacial amphitheatres provide long-term sedimentary records that span multiple glacial and interglacial stages, the preservation potential of deposits and landforms, formed during each of these stages, is generally low (Gibbons et al., 1984; Cremaschi, 1987; Bini & Zuccoli, 2004; Monegato et al., 2017). In fact, glacier front advances are generally able to destroy the most of previous stage deposits, making it difficult to infer processes from the sedimentary record, including those governing sedimentation in proglacial environments (Jopling & McDonald, 1975; Ehlers & Gibbard, 2004; Carrivick & Tweed, 2013). On the other hand, smaller moraine systems developed during the last glacial phases of the Pleistocene are comparatively better preserved and allow for more detailed stratigraphic reconstructions, which are meaningful to better understanding time-space relationship between glacial and proglacial environments (Accorsi et al., 1990; Monegato & Ravazzi, 2018; Palmer et al., 2019).

The sensitivity of glaciolacustrine systems to ice-mass and landscape changes (Carrivick & Tweed, 2013) makes them valuable archives of glacier dynamics, particularly of deglaciation phases (i.e., Shaw, 1975; Orombelli & Gnaccolini, 1978; Colman et al., 1994; Winsemann et al., 2009, 2018; Nehyba et al., 2017; Lang et al., 2018, 2021; Kurjanski et al., 2021). Here, proglacial lakes act as sedimentary sinks, in which the glacier discharges huge amounts of sediments, with important spatio-temporal variations in the flow regime (Marren, 2005; Fielding, 2006; Duller et al., 2008; Cuffey & Paterson, 2010; Carling, 2013; Dowdeswell et al., 2015; Fitzsimons & Howarth, 2018; Lang et al., 2021). They can be viewed as low-energy lakes receiving sediments from both glacial and fluvial-glaciofluvial input via a diversified range of steady to more episodic (e.g., slow fallout from the water column, density flows, supercritical flows) flows (Church & Gilbert, 1975; Gustavson et al., 1975; Bennet et al., 2002; Palmer et al., 2019; Lang et al., 2017, 2021). The prevailing depositional process is largely determined by climate-driven modifications of the glacier and landscape (Bennett et al., 2002; Fielding, 2006; Winsemann et al., 2009, 2018; Palmer et al., 2019; Lang et al., 2021), which typically results in strongly cyclical facies associations that may be used to reconstruct seasonal to secular limnological and glaciological changes (Bersezio et al., 1999; Pawlowsky et al., 2013; Palmer et al., 2019).

This contribution reports on glaciolacustrine deposits of the Upper Pleistocene Adige Moraine Amphitheatre (AMA), also known as the Rivoli Veronese moraine system (Cremaschi, 1987), which was part of the greater Adige-Sarca glacial system of Northern Italy during most of Pleistocene glaciations. The latter consists in the piedmont area by two sets of frontal-moraine systems characterized by a semi-circular amphitheatre-like shape, the Garda and Adige Glacial Amphitheatres (Fig. 1 and 2; Penck & Brückner, 1909; Venzo et al., 1969; Bini & Zuccoli, 2004; Bini, 2012). Located at the termination of the confined Adige Valley and at the foothills of the Southern Alps, the AMA is one of the smallest yet best-preserved terminal moraine systems of continental Europe (i.e., Penck & Brückner, 1909; Venzo, 1961; Cremaschi, 1987; Bini, 2012). Indeed, most of its recent construction, occurred during the Last Glacial Maximum (LGM; Accorsi et al., 1990), preserved it from

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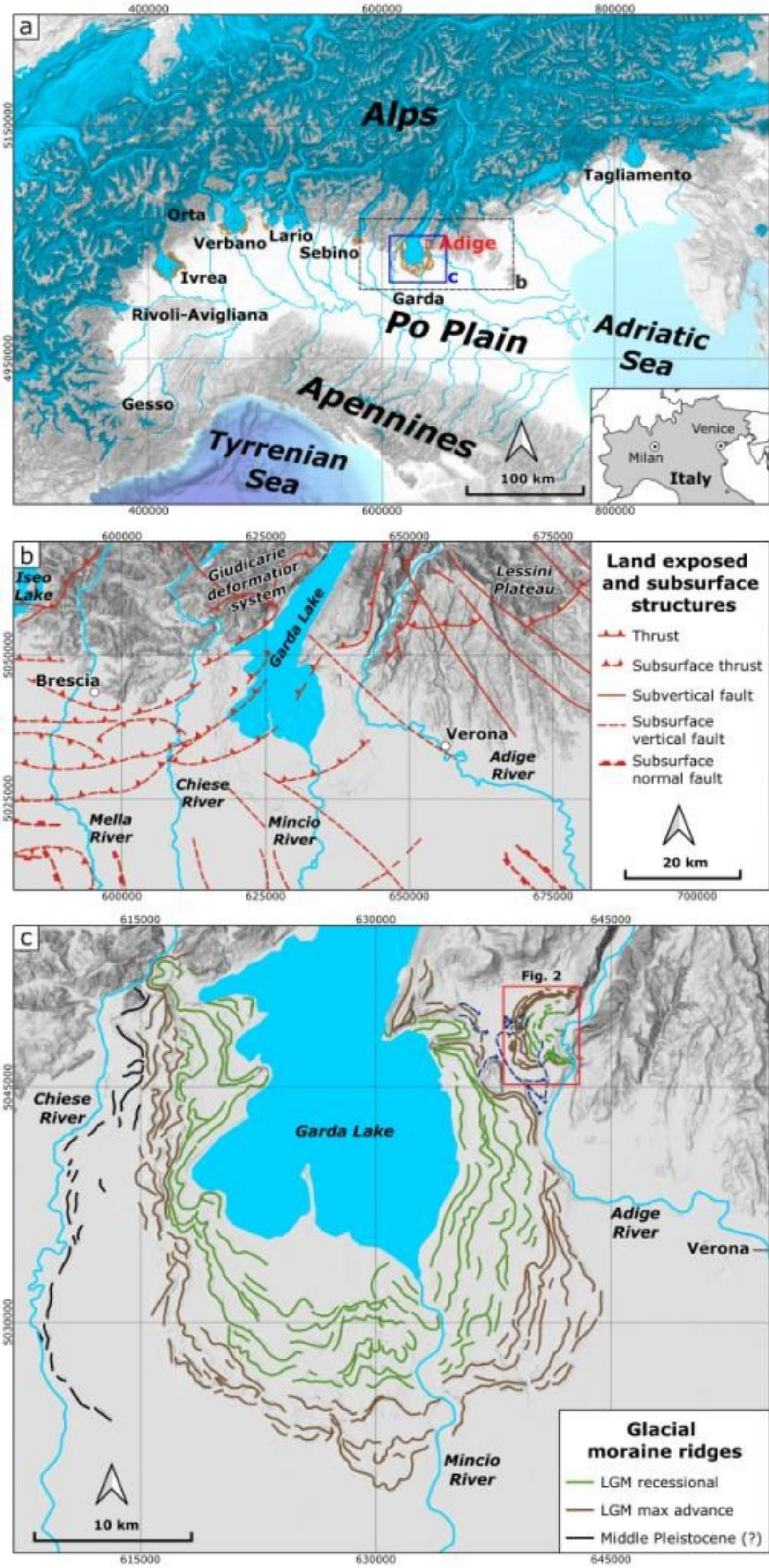


Fig. 1 - (a) Map of the Alps illustrating the distribution of the maximum ice extent during Middle-Upper Pleistocene, highlighting the main glacial amphitheatres of North Italy (modified after Ehlers & Gibbard, 2004; Margottini & Vai, 2004; Bini, 2012; Ivy-Ochs, 2015; Ivy-Ochs et al., 2018). Countries' borders from "World Country" (Porto Tapiquén, 2015). (b) Regional structural setting of the Southern Alps and Po Plain (hydrography and 20m resolution DEM from ISPRA, 2012; redrawn after Bigi et al., 1990; Fantoni et al., 2004; Scardia et al., 2014). (c) Extension and age attribution of the moraine ridges formed during the Pleistocene by the Adige-Sarca glacial system. With dotted lines the main meltwater pathways in the area comprised between the two amphitheatres (redrawn after Venzo, 1957, 1961, 1965; Venzo et al., 1969; Cremaschi, 1987; Accorsi et al., 1990; Bini & Zuccoli, 2004; Monegato et al., 2017). Marked by the red rectangle the AMA (Fig. 2).

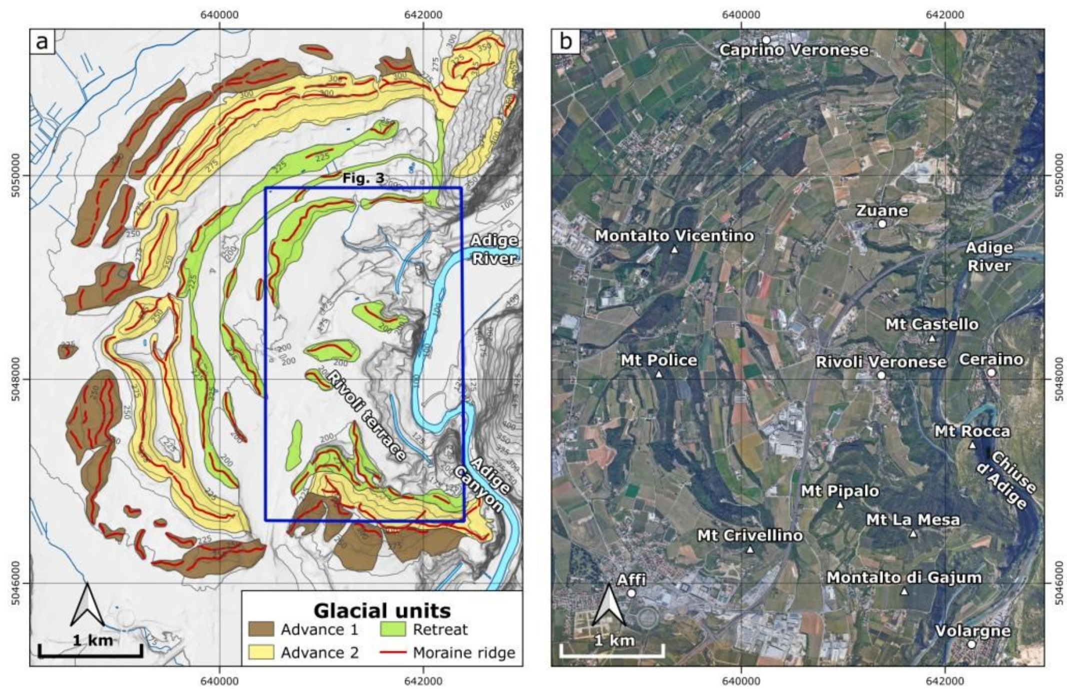


Fig. 2 - (a) Interpretation for the relative age attribution of the glacial units of the AMA; noting Adige canyon is also known as Chiuse d'Adige canyon in the text (Fig. 2b). The investigated area discussed in this paper is marked by the blue rectangle (Fig. 3). (b) Satellite image of the Adige River Glacial Amphitheatre with topological references (Google Satellite, CNES/Airbus, 2021).

reworking and partial dismantling by further glacial advances as much as by post-glacial processes. Because of subsequent phases of glacial retreat, terminal proglacial lakes formed in the innermost area of the AMA (Venzo, 1961; Venzo et al., 1969; Accorsi et al., 1990) and hosted glaciolacustrine sedimentation in a range of sub-environments (Fig. 2 and 3). The resulting deposits are almost well-preserved, although the outcrops are usually not extensive, and provide a valuable record of LGM glaciolacustrine sedimentation which may help constraining dynamics and mechanics of the final retreat of the Adige Glacier.

This work aims at providing constraints on the paleogeography of the latest LGM advance of the Adige Glacier and describing processes acting at the onset of the deglaciation. To accomplish this task, we mapped the spatial distribution of the sedimentary facies associations making up the proglacial deposits of the LGM Adige Glacier through the combined use of geomorphological and geological mapping and sedimentary facies analysis of type sections and key outcrops.

2. GEOLOGICAL SETTING AND PREVIOUS WORKS ON THE QUATERNARY EVOLUTION OF THE GARDA AND ADIGE MORAINE AMPHITHEATRES

From a geological point of view, the Adige Valley belongs to the Southern Alps domain, a fold-and-thrust belt formed during the Alpine orogenic phase (Laubscher, 1985; Picotti et al., 1995; Scardia et al., 2015). To the East, the Garda and Adige Glacial Amphitheatres are bounded by the Lessini Plateau (Fig. 1b), a structural block gently tilted towards the Po Plain (Fantoni et al., 2004; Scardia et al., 2015). Specifically, the lower Adige Valley is developed along the "Giudicarie deformation system", a NNE-SSW trending polyphasic fault system (Fig. 1b), connecting the Lessini Plateau to the deeper western Lombardian basin (Venzo et al., 1969; Accorsi et al., 1990; Fantoni et al., 2004; Bassetti & Borsato, 2005). The bedrock outcropping in the AMA area belongs to the Upper Triassic - Upper Eocene 'so called' Venetian series and is composed by limestones, marly limestones, and marls of Jurassic - Cretaceous age (Venzo, 1961; Venzo et al., 1969). The "Giudicarie deformation system", active since the Mesozoic until the Quaternary, coupled with differential subsidence, influenced the geomorphological evolution of the Adige Valley, resulting in an over-excavation of the lower part of the valley (Venzo et al., 1969; Sorbini et al., 1984; Accorsi et al., 1990).

Many authors investigated the dynamics of the Garda Glacier, reconstructing multiple glacial advances from the Early Pleistocene up to the LGM two-fold glacial advance, which separated the Garda and Adige glaciers (Fig. 1c) (i.e., Nicolis, 1899; Penck & Brückner, 1909; Cozzaglio, 1933, 1934a, 1934b, 1939; Venzo,1957, 1961, 1965; Habbe, 1960, 1969; Mancini, 1960, 1969; Fraenzle, 1965; Venzo et al., 1969; Cremaschi, 1987; Cremaschi et al., 1987; Accorsi et al., 1990; Bini & Zuccoli, 2004; Ravazzi et al., 2014; Monegato et al., 2017). Specifically, the area has been intensively investigated since the 19^{th} century (Paglia, 1861; Sacco, 1896; Nicolis, 1899), leading to early recognition of the hills surrounding the Garda Lake as

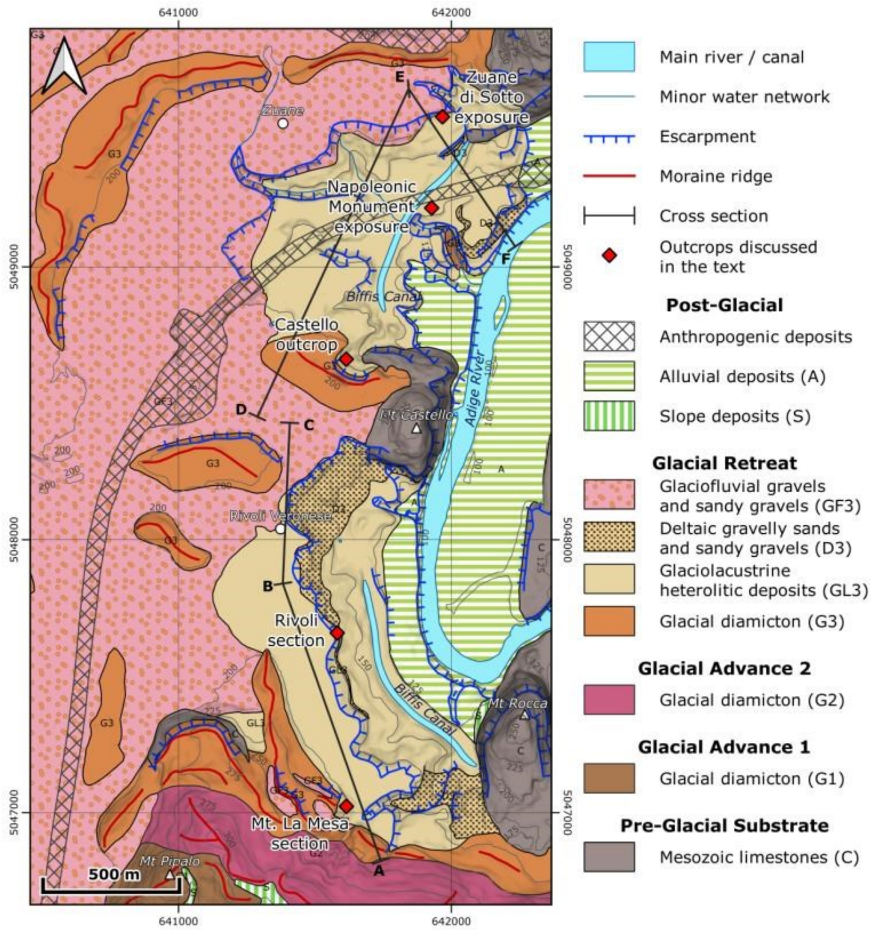


Fig. 3 - Quaternary geological sketch map of the AMA innermost moraine ridge. The glacial units are summarized into three group, based on morphostratigraphic criteria: Glacial Advance 1, Glacial Advance 2, Glacial Retreat. Furthermore, we reported also Pre-Glacial Substrate (Mesozoic limestones, Venzo et al., 1969; Accorsi et al., 1990) and Post-Glacial deposits. The outcrops and stratigraphic sections described in this paper are highlighted. Smaller kame terraces are highlighted on the northern flank of Mt La Mesa by glaciofluvial deposits (GF3). Cross sections are represented in Fig. 5.

Quaternary moraines (Tab. 1). Penck & Brückner (1909) framed these into their four-stage (Günz - Mindel - Riss - Würm) glaciation schema, which was later adopted with slight modifications by the detailed works of Cozzaglio (1934a, 1934b, 1939) and Venzo (1957, 1961, 1965). However, the chronostratigraphic attribution of these moraine ridges has been since long debated, highlighting the limitations of Penck & Brückner's stratigraphic schema (Cremaschi, 1987; Bini & Zuccoli, 2004). A synthesis of alternative hypotheses on stratigraphic attribution and significance of the glacial deposits in the Garda Glacial Amphitheatre is reported in Table 1. Starting from the seminal work of Penck & Brückner (1909), both relatively younger and older glacial deposits have been consistently recognised in more internal (closer to the Garda lake) and more external locations, respectively (Fig. 1c). Many scholars (Tab. 1) follow a substantial homogeneity in stratigraphic classification, modifying the four-stage glaciation schema by revising it and adding or removing stages of minor advances (i.e., Würm I, II, III; Riss I, II, etc.; Cacciamali, 1914; Cozzaglio, 1932; Venzo, 1957, 1961, 1965; Venzo et al., 1969). Venzo (1957) recognized and separated the innermost moraine ridges based on their geological features - quite different between them and from the rest of the amphitheatre - but he was not able to move out the four-stage glacial schema (Bini & Zuccoli, 2004). Cremaschi (1987) reconstructed the Garda Glacier history on correlations based on lithostratigraphy, magnetostratigraphy, paleopedostratigraphy and archeostratigraphy. He also further applied the correlations in a chronostratigraphic framework, recognizing 5 phases of glacial advance in the Garda Amphitheatre from the Early Pleistocene to the Late Pleistocene (Tab. 1). Furthermore, he hypothesized the subdivision of the last glacial advance into two substages, with the first corresponding to the main moraine ridge (Cremaschi, 1987). Bini & Zuccoli (2004) and Bini (2012) adopted the concept of Allostratigraphic Unit (Richmond, 1962; Bini 1997a) to reconstruct the chronology, evolution, and palaeogeography of the geological deposits. Starting from the methodologies applied in the survey of the Verbano and Lario moraine amphitheatres (Fig. 1a; Bini, 1987; Bini 1997b; Bini et al., 2001; Bini et al., 2014),

Sacco (1896)	Penck & Brückner (1909)	Cacciamali (1914)	Cozzaglio (1932, 1934a, 1934b, 1939)	Venzo (1957, 1961)	Fraenzle (1965)	Venzo (1965); Venzo et al. (1969)	Cremaschi (1987)	Bini & Zuccoli (2004); Bini (2012)	Ravazzi et al. (2014)	Monegato et al. (2017)
Only one glacial period	Würm	Würm	Würm	Würm II	Würm	Würm II	Solferino stage (Late Pleistocene)	Garda Alloformation (LGM, Late Pleistocene: MIS 2)	Manerba advance (end of LGM)	Unit B - recessional stage (LGM, Late Pleistocene)
Villafranchian	Riss	Riss II	Riss	Würm I	Riss	Würm I	Sedena stage (late Middle Pleistocene)	Puegnago Alloformation (Middle-Late Pleistocene: MIS 18-4)	LGM	Unit A - maximum advance (LGM, Late Pleistocene)
	Mindel	Riss I	Mindel	Riss II	Mindel	Riss II	Carpenedolo stage (Middle Pleistocene)	San Zeno Alloformation (Middle-Late Pleistocene: MIS 18-4)	Middle Pleistocene	Pre-LGM
	Günz	Mindel	Günz (fluviatile)	Riss I		Riss I	Faita stage (Early Pleistocene - early Middle Pleistocene)	San Pietro Alloformation (Middle-Late Pleistocene: MIS 18-4)		
		Günz (fluvioglacial)		Mindel II		Mindel II	Ciliverghe stage (Early Pleistocene)	Monte Forca Alloformation (Middle-Late Pleistocene: MIS 18-4)		
				Mindel I		Günz II		Monte Cervo Alloformation (Middle-Late Pleistocene: MIS 18-4)		
				Günz		Günz I		Monte Serina Alloformation (Middle-Late Pleistocene: MIS 18-4)		
						Mindel		Cà Dell'Ava 2 Formation (Lower Pleistocene: MIS 22-20)		
								Cà Dell'Ava 1 Formation (Lower Pleistocene: MIS 22-20)		
								Ponte Clisi 2 Formation (Lower Pleistocene)		
								Ponte Clisi 1 Formation (Lower Pleistocene: MIS 100-96)		
								Ciliverghe Alloformation (Lower Pleistocene: MIS 100-96)		

Tab. 1 - The different stratigraphical attributions of the glacial stages of the Garda Glacial Amphitheatre.

they recognized up to 12 allo- and lithostratigraphic units in the western portion of the Garda Glacial Amphitheatre, leading to the individuation of 8 different glaciations (sensu Richmond, 1986) from the Lower Pleistocene (MIS 100-96) to the LGM (MIS 2) (Bini & Zuccoli, 2004; Bini, 2012).

There is widespread consensus in literature that during the Pleistocene glaciations, the Garda and Adige glaciers were part of the Adige-Sarca glacial system, a larger valley glacier bifurcating North of the city of Trento. One larger tongue descended the Sarca Valley forming a piedmont glacier in correspondence to the present-day Garda Lake, while a smaller glacier developed along the Adige Valley (Fig. 1a) (Lenotti, 1980; Cremaschi, 1987; Bini, 2012; Ravazzi et al., 2014). The extent and complexity of Adige-Sarca glacial system - c. 15.000 Km^2 during the LGM, spanning a range of sedimentary, volcanic, magmatic, and metamorphic terranes - explains the very varied lithological composition of its deposits. These include allochthonous clasts of rhyolites, porphyries, granitoids and meta-granitoids derived from the erosion of volcanic bodies in the Eastern Alps and from the alpine crystalline basement (Baroni & Cremaschi, 1987; Bini & Zuccoli, 2004; Ravazzi et al., 2014). To the South, the Garda and Adige glaciers were probably confluent for most of the Pleistocene glaciations, forming a single glacial amphitheatre (the pre-LGM Garda Glacial Amphitheatre; Bini & Zuccoli, 2004). The two glaciers were in fact individual glacial bodies only during the last glacial advance, which terminated with separated end-moraine systems (Garda and Adige Moraine Amphitheatres; Fig. 1) (Cremaschi, 1987; Bini, 2012).

Recently, several scholars reinvestigated many of the Italian Alpine Pleistocene glacial amphitheatres and proposed a two-fold glacial advance model during the LGM at the Southern Alpine margin (Bini, 1987; Cremaschi, 1987; Monegato et al., 2007; Gianotti et al., 2008, 2015; Bini et al., 2014; Ivy-Ochs et al., 2018; Monegato & Ravazzi, 2018; Rossato et al., 2018; Braakhekke et al., 2020; Kamleitner et al., 2022). Monegato et al. (2017) identified fresh geomorphological, stratigraphical, and chronological evidence extending the validity of the model to the Garda Glacial Amphitheatre (Fig. 1c). It is therefore reasonable to attribute a similar LGM behaviour to its Adige Glacier companion (Fig. 2 and 3).

2.1. Focus on AMA: geology, geomorphology and historical background

The study area occupies an area of circa 6 km^2 belonging to the innermost part of the AMA system, which lies at the outlet of the Adige Valley and to the East of the Garda Glacial Amphitheatre (Fig. 1). Yet, the smaller Adige Glacier impacted heavily on the surrounding landscape, occupying with its amphitheatre an area of more than 15 km^2 (Fig. 2). The elevation of the area is comprised between 87 and 460 m a.s.l., with an average of 218 m a.s.l. (Fig. 2 and 3). The landscape is characterized by the presence of 7/8 semi-circular concentric moraine ridges, arranged in an "amphitheatre" shape, that border a series of glaciofluvial and glaciolacustrine plains/terraces, downscaling towards the current course of the Adige River (Fig. 4). Figures 1c and 2a show the distribution of the AMA moraine ridges: the outer part of the system includes two major moraine ridges; in the inner amphitheatre, ridges decrease in elevation towards the valley and become more discontinuous (Fig. 3) (Penck & Brückner, 1909; Venzo,1961; Cremaschi, 1987; Accorsi et al., 1990). Furthermore, in the southern sector, the "Chiuse d'Adige" canyon is one of the main features (Fig. 2): it is a small pathway bordered by very steep oolitic limestone walls characterized by notches on different levels and a meander geometry, developed due to the interaction of karst and fluvial pro-

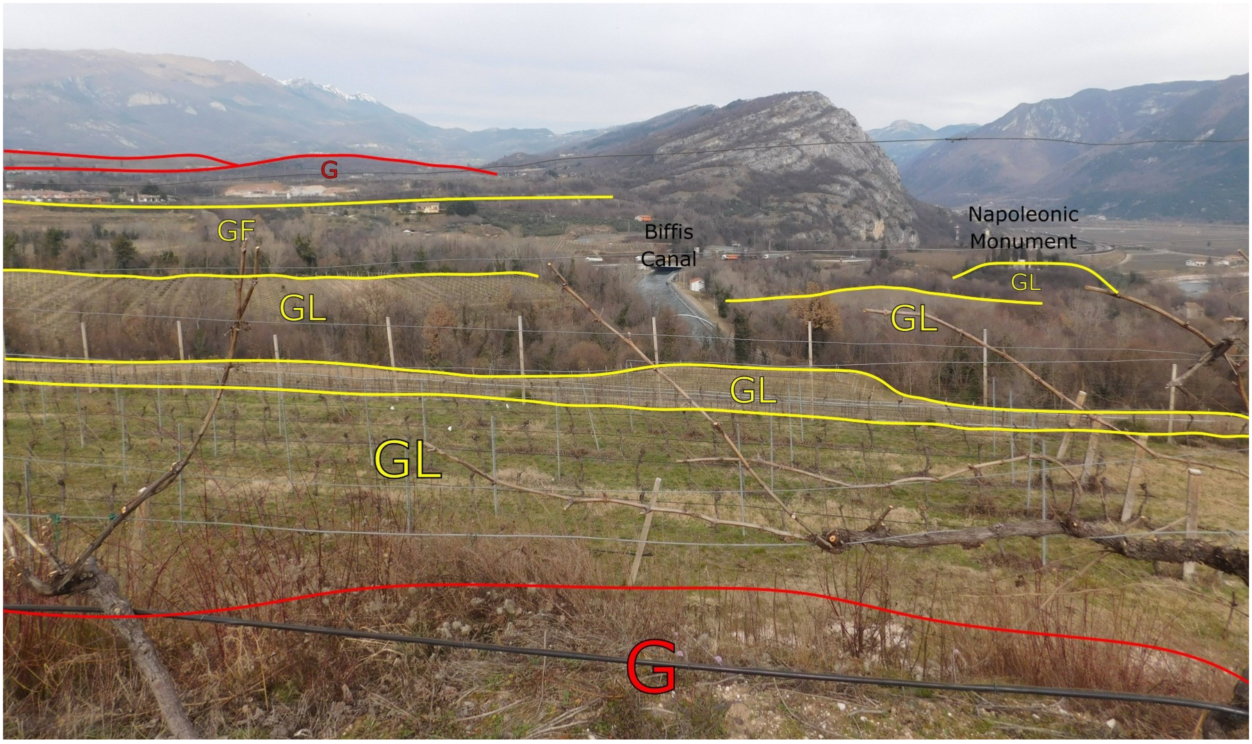


Fig. 4 - Panoramic view from Mt Castello to the North (see Fig. 2 for the location). On the landscape are highlighted the moraine ridge and glacial deposits (G and red lines), particularly in foreground and in background. In the middle a series of glaciolacustrine and glaciofluvial (GL) terraces are shown.

cesses. Moreover, near Caprino Veronese, north of the AMA, older till deposits are found which, due to the absence of absolute dating, can be doubtfully attributed to the Early - Middle Pleistocene (Cozzaglio, 1933, 1934a; Cremaschi, 1987; Accorsi et al., 1990).

In Table 2 we report the correlations between different stratigraphies adopted in previous studies (Nicolis, 1882; Penck & Brückner, 1909; Cozzaglio, 1933, 1934a; Habbe, 1960; Venzo, 1961; Venzo et al., 1969; Cremaschi, 1987; Accorsi et al., 1990; Ravazzi et al., 2014). In the first work describing the area, the “Carta Geologica della Provincia di Verona” (“Geological map of the Verona Province”; Nicolis, 1882), the author recognized glacial deposits and moraines surrounding Rivoli Veronese town but was not able to separate different glaciations. Penck & Brückner (1909), in their seminal work on Alpine glaciers, attributed the outermost moraine ridges to the Riss glaciation, and the inner ones to the Würm period. Later works followed this concept with some modifications, moving the attribution of one or more moraine ridges to the Würm or Riss glaciations. Cozzaglio (1933) hypothesised the existence of a Mindel age moraine in the subsoil in front of the AMA; furthermore, Cozzaglio recognized muddy sediments in the inner Würm moraine ridges and interpreted them as lacustrine-basinal sediments. Habbe (1960) attributed all the amphitheatre to the Riss glaciation based only on pedological analyses.

In his comprehensive work on the Quaternary geology of the Garda and Adige Glacial Amphitheatre, Venzo (1961) suggested a two-fold glaciation model to explain the formation of the Quaternary deposits of the AMA, respectively to the Riss and Würm glacial expansions. To explain the presence of more than two major moraine ridges (Fig. 2), Venzo (1961) subdivided both glaciations into multiple phases of advance and retreat and attributed the outer moraine ridges to the Riss glaciation and the inner system moraine ridges to the Würm glaciation. He further divided the latter into three stages (Würm I to Würm III), suggesting that the moraine system acted as a dam during the Würm II-Würm III interstage and triggered the formation of ice-marginal lakes at the mouth of the Adige Valley (Venzo, 1961). However, in his following work (Venzo et al., 1969), he simpli-

Nicolis (1882)	Penck & Brückner (1909)	Cozzaglio (1933, 1934a)	Habbe (1960)	Venzo (1961)	Venzo et al. (1969)	Cremaschi (1987)	Cremaschi in Accorsi et al. (1990)	Ravazzi et al. (2014)	This work
Only one glacial period	Würm	Würm	Riss	Würm III	Würm	Solferino stage (Late Pleistocene)	Fiffaro unit (Upper Pleistocene)	LGM	Glacial retreat
				Würm II	Riss				
	Riss	Riss		Würm I			M.te Police unit (Upper Pleistocene)		Glacial advance 2
				Riss		Sedena stage (late Middle Pleistocene)	M.te Crivellino unit (Middle Pleistocene)		Glacial advance 1
		(Mindel)							

Tab. 2 - The different stratigraphical attributions of the glacial stages of the AMA.

fied his relative chronology and attributed the previous Riss, Würm I and Würm II to the Riss glaciation, leaving the Würm III as the only deposits of the Würm glaciation (Tab. 2). Such revisions come after the completion of the survey of both the Garda and Adige Glacial Amphitheatres (completed in 1965: Venzo, 1965) and for reasons of scale. Lenotti (1980) just gave some passing remarks to the discussion of the AMA formation and referred to previous authors.

More recent investigations, based on the above-mentioned criteria for the classification of the Garda Glacial Amphitheatre (Cremaschi, 1987), permitted to attribute the outermost moraine ridge to the Sedena stage (late Middle Pleistocene), and all the inner ones to the Solferino stage (Late Pleistocene) (Cremaschi, 1987). Later, in Accorsi et al. (1990) Cremaschi made a review of the AMA and reattributed the outermost moraine ridge to the M.te Crivellino unit (Middle Pleistocene), the main moraine ridge to the M.te Police unit (Upper Pleistocene) and the other ones to the Fiffaro unit (Upper Pleistocene). In this framework, the presence of glaciolacustrine deposits is related to the glaciofluvial deposits of the Late Glacial paleochannel of the Adige River (Rivoli unit) (Accorsi et al., 1990). The presence of occasional strips of older deposits in the AMA area is registered and related to the pedostratigraphical description of loess deposits (Accorsi et al., 1990). Ravazzi et al. (2014) attributed all AMA moraine ridges to the LGM, without distinction of different advance phases, unlike the Garda Glacial Amphitheatre (Tab. 1 and 2).

Other information on the evolution of the AMA come from studies involving the surrounding landscape. Sorbini et al. (1984) surveyed the Venetian Plain South of Verona and downstream the AMA. They reported large boulders embedded in alluvial deposits cropping out in the Venetian Plain, characterized by dimensions up to 2 m in diameter and petrography coherent to the Adige-Sarca glacial system (Sorbini et al., 1984). These features, combined with their position downstream circa 20 km South from the AMA and 15 km East from the maximum glacial expansion of the Adige-Sarca glacial system, suggest that the boulders are related to the final stages of the Adige glaciofluvial fan aggradation (Sorbini et al., 1984).

3. METHODS

Mapping, data collection and interpretation proceeded through the following path: remote sensing in-

Facies association	Code	Lithofacies	Interpretation
G	Dmm	Matrix-supported, massive diamicton	Deposition from debris flows originating from the ice-front or deposited as meltout/flow tills
G	Dcm	Clast-supported, massive diamicton	Deposition from more sorted debris flows originating from the ice-front or deposited as flow tills
G	Dms(c)	Matrix-supported, stratified diamicton with evidence of current reworking	Deposition as flow till with evidence of traction current (cross-stratification, imbrication)
GF	Gsi	Clast-supported, imbricated gravel	Deposition from tractional bedload flows in a subaerial channel
GF + D	Gt	Trough cross-stratified gravel	Deposition of migrating 3D dunes or transverse bars, produced from tractional bedload flows or sustained turbidity currents
GF + D	Gp	Planar cross-stratified gravel	Deposition of migrating 2D dunes or transverse bars, produced from tractional bedload flows or sustained turbidity currents
D (+GF)	Gfu	Normally graded gravel to granule/sand	Deposition from waning high-density turbidity currents
D	Gm	Clast-supported, massive gravel	Deposition from hyperconcentrated density flows
GL	St	Trough cross-stratified sand	Deposition of migrating 3D dunes, produced from subcritical tractional bedload flows or sustained turbidity currents generated from the delta
GL	Sp	Planar cross-stratified sand	Deposition of migrating 2D dunes or transverse bars, produced from subcritical tractional bedload flows or sustained turbidity currents generated from the delta
GL	Sr	Planar or ripple cross-laminated sand	Traction deposition of migrating 2D ripples, from sustained turbidity currents generated from the delta
GL	Sh	Planar-parallel stratified sand	Deposits of upper-flow regime plane bed, formed by traction deposition from high-density turbidity currents generated from the delta
GL	Se	Erosional scours with intraclasts	Cut and fill deposition from high-density turbidity currents or chutes-and-pools
GL	Sfu	Normally graded sand to mud	Deposition from waning surge-like or more sustained low-density turbidity currents
GL	Fl	Finely laminated silt and clay	Traction and fall out deposition from waning low-density turbidity currents or fall out deposition from hypopycnal and homopycnal low-density turbidity currents
GL	Flv	Rhytmites of silt, clay and fine sand	Traction and fall out deposition from waning low-density turbidity currents or fall out deposition from hypopycnal and homopycnal low-density turbidity currents
GL	Fm	Massive silt and clay	Deposition from hyperconcentrated and concentrated sediment-density flows and turbidity currents

Tab. 3 - Facies associations, facies types and codes.

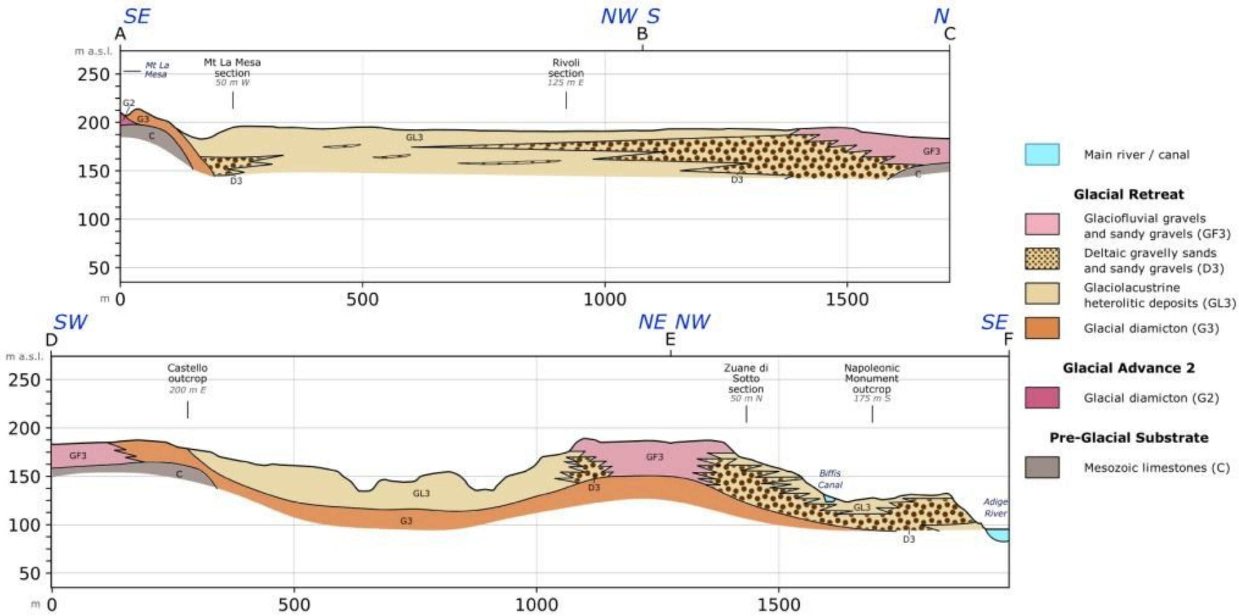


Fig. 5 - The two stratigraphic cross sections of the AMA innermost moraine ridge traced in Fig. 3, showing the morphostratigraphy of the southern (A-B-C section, above) and northern (D-E-F section, below) sectors of the investigated area. Vertical exaggeration is by two.

vestigation, field survey with identification and descryption of key stratigraphic sections and outcrops, facies interpretation and morphostratigraphic correlations. For remote sensing investigations, we made combined use of 1:5.000 and 1:10.000 topographic maps and a Digital Elevation Model (DEM) with horizontal resolution of 5 m (Regione Veneto, 2018). All outcrops and stratigraphic sections (Fig. 3 and S1) were mapped in WGS 84/UTM zone 32N coordinate system using QGIS (versions 3.4 and 3.16: QGIS development team, 2019, 2021). Each outcrop and stratigraphic section was associated to a code and georeferenced (material available through supplementary material - Fig. S1, Tab. S1). The deposits were described by their properties (Bini, 1990), including context, size and geometry of the outcrop, definition, grain size, texture, consolidation and cementation, clast morphology and petrographic composition, sedimentary structures, colours (with the Munsell Soil Color Charts code), and sedimentary facies defined following classical schemes (Miall, 1977, 1978, 1996; Eyles & Miall, 1984; Bini, 1990; Bennet et al., 2002; Johnsen & Brennand, 2006; Winsemann et al., 2009, 2018; Bini et al., 2014; Lang et al., 2017, 2021; Lee, 2018; Palmer et al., 2019; Kurjanski et al., 2021). Several sedimentary facies were identified (Tab. 3), which were later grouped into four facies associations diagnostic of as many depositional settings (Section 4.1), based on their spatial distribution, geomorphological meaning (Section 4.2), occurrence in key outcrops and logged stratigraphic sections (Section 4.3). The stratigraphic interpretation of the recognized units was extrapolated through the interpolation between DEM, topography, and outcrops data (Section 4.4), heading to a comprehensive morphostratigraphy of the AMA innermost moraine ridge (Fig. 3 and 5; Gibbons et al., 1984; Ivy-Ochs et al., 2018).

4. RESULTS

4.1. Facies associations

This section reports the four different types of facies associations described in the study area, and details the distribution, properties, and significance of facies associations.

Glacial diamictons (Facies association G)

This facies association consists of a variety of matrix- and clast-supported gravelly diamictons forming moraine ridges, such those shown in the map of Figure 3. The deposit is represented by generally poorly-sorted sediment admixtures (Fig. 6a-b) with observed thicknesses up to 6 m highly variable textures (Tab. 3). Gravel-grade clasts represent the dominant volumetric fraction, accompanied with variable proportions of sand and mud. Sands locally form discontinuous beds up to 0.6 m-thick with lateral continuity less than a few metres.

Internally, these deposits are massive, except for relatively better sorted lenses, which can show cross-stratification and clast imbrication (Fig. 6a-b; Tab. 3). Clasts are angular to well-rounded, with average size of 16 cm and max size of 150 cm. The matrix grain-size ranges from clay to coarse sand, with a colour varying from 7.5YR 7/2 (pinkish gray) to 10YR 6/3 (pale brown). The lithological composition of the coarse fraction is well-diversified (polygenic gravel), with abundant limestone clasts (60-70%), a moderate quantity of purple and green rhyolites-porphyries (20-30%), and less frequent basement lithologies (orthogneiss and quarzitic paragneiss, 10-20%). All clasts usually show very poor to poor weathering.

Occurrence and interpretation: The sedimentary character and geometry of these diamicton deposits suggest they can represent melt-out and, secondarily, flow tills accumulated at the ablating ice-front. On the

Fig. 6 - Examples of facies from glacial diamictons, glaciofluvial and deltaic facies associations. (a) Matrix-supported, stratified diamicton with evidence of current reworking, ascribed as flow till (northern flank of Mt La Mesa, ID: 44). (b) Matrix-supported, massive diamicton, ascribed as melt-out till (North of Zuane, ID: 127). (c) Planar and through cross-stratified gravel (North-East of Zuane di Sotto exposure, ID: 110). (d) Clast-supported, imbricated gravel infilling a channel scour in matrix-supported massive diamicton (interpreted as till), highlighted by different grain sizes, clast-supported texture, and cementation (South-East of Mt Castello, ID: 41).

other hand, cross-stratified and better-sorted deposits are interpreted as the result of traction from stream waters able to rework sediments so as to form medium-scale bedforms (Bini, 1990; Winsemann et al., 2009; Lee, 2018).

Glaciofluvial deposits (Facies association GF)

This facies association is composed of clast-supported gravels and sandy gravels, forming rather monotonous sections up to at least 10 m (Tab. 3). The stratification of these deposits lays horizontally. The finer-grained component of the deposits is represented by up to 40% of sand and c. 10% of silt. Beds are erosionally based, with scours up to several tens of cm-deep or channelised (composite) basal surfaces. Internally, the deposit can be structured, with through- and planar cross-stratifications and occasional clast imbrication (Fig. 6c-d), and ungraded to crudely graded (Fig. 7b).

Clasts are sub-angular to well rounded, with average size of 8 cm and max size of 50 cm. Matrix grain-size is comprised between silt and coarse sand, with colour varying from 7.5YR 6/4 (light brown) to 5YR 6/3 (light reddish brown) to 5YR 3/4 (dark reddish brown). The lithological composition of the coarse fraction is well-diversified (polygenic gravel), with abundant limestone clasts (50-70%), a moderate quantity of purple and green rhyolites-porphyries (20-30%), and less frequent basement lithologies (orthogneiss and quarzitic paragneiss, 10-20%). Disregarding their composition, clasts show very poor to poor weathering.

Occurrence and interpretation: This facies association occurs in the uppermost terraced sitting on top of glacial diamictons of Facies association G (Section 4.1.1). Sedimentary structures and depositional geometries are suggestive of deposition in a glaciofluvial setting at the glacier ice-front, in which fluvial processes and traction organise sediments in a range of fluvial bar types (Jopling & McDonald, 1975; Bersezio et al., 1999; Bennet et al., 2002; Winsemann et al., 2018; Lang et al., 2021; Kurjanski et al., 2021).

Deltaic deposits (Facies association D)

This facies association is composed of gravelly sands and relatively rarer clast-supported gravels forming bedsets up to c. 5 m-thick (Tab. 3). The stratification of these deposits lay horizontally in all outcrops

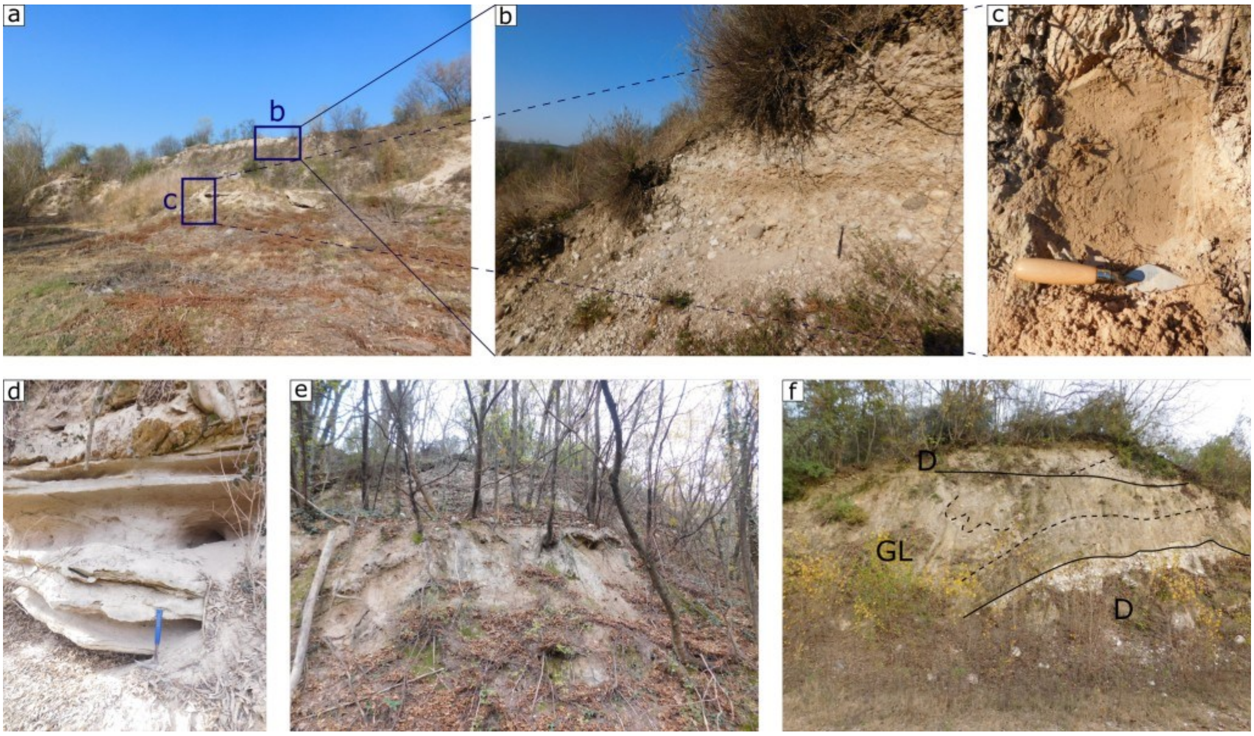


Fig. 7 - Outcrops from the northern investigated area. (a) Global view of the Zuane di Sotto exposure. (b) Normally graded pebbly gravel to granule and sand (deltaic Facies association D), particular from the upper Zuane di Sotto exposure. (c) Massive silt (glaciolacustrine Facies association GL), particular of the lower Zuane di Sotto exposure. (d) "Napoleonic Monument" exposure, showing planar- and cross-stratified sand (glaciolacustrine Facies association GL). (e) Lowermost portion of the Napoleonic Monument exposure, composed by massive mud (glaciolacustrine facies association GL). (f) Outcrop near Napoleonic Monument, composed by deltaic and glaciolacustrine facies associations; the dotted lines highlight the bedding, the solid lines highlight the boundaries between facies associations. Notice the deformed stratification in the sandy deposits, interpreted as slumping.

except from one locality (Napoleonic Monument exposure in Section 4.3; Fig. 7f), where it dips toward the NW with angles up to 20°. The finer-grained component of the deposits is represented by up to 40% of sand and c. 10% of silt. Bed bases are flat to slightly erosional. Internally, the deposit can be either massive (Fig. 8a) or structured, with through- and planar cross-stratifications (Fig. 7f, 9c-e) suggestive of migrating 2D and 3D dunes, and ungraded to normally graded (Fig. 9f and 10d). Notably, in the outcrop with inclined stratification these deposits are chiefly massive or normally graded, with little evidence of internal organisation, and interbedded with finer-grained glaciolacustrine deposits. Here, some beds show evidence of soft sediment deformation, likely related to incipient gravity-driven slumping.

The character of gravel-grade clasts is similar to that of Facies association GF except for a relatively higher roundness and finer grain-size.

Occurrence and interpretation: This sedimentary facies association is exposed at different localities along the slopes facing the Adige River (Fig. 3) and are locally vertically and associated with glaciolacustrine deposits (Facies association GL). Massive to normally graded beds with inclined bedding and soft sediment deformations, such those cropping out at the Napoleonic Monument exposure (Fig. 7f; Section 4.3), can be interpreted as the product of deposition from a range of subaqueous sediment gravity flow types (including debris flows, hyperconcentrated turbidity currents and mass movements) in the relatively steep upper part of a delta front (Bersezio et al., 1999; Bennet et al., 2002; Johnsen & Brennand, 2006; Winsemann et al., 2009, 2018; Lee, 2018; Kurjanski et al., 2021). On the other hand, structured deposits interbedded with glaciolacustrine deposits (e.g., in the Rivoli section) resemble hyperpycnal bedload facies B1-B2 of Zavala and Pan (2018) and reported occurring on glaciolacustrine deltas by Lang et al. (2017), and are thus better interpreted as the product of deposition from long-lived, flood-generated density flows in pro-delta settings (i.e., Powell, 1990).

Glaciolacustrine deposits (Facies association GL)

This facies association form a few to several m-thick bedsets which locally sandwich (e.g., in the Rivoli Section, Fig. 9) deltaic deposits (Facies association D). It is represented by very thin- to medium-bedded normally graded deposits including a range of sandy gravels to gravelly sands and very fine well-sorted sands, silts and clays (Fig. 7c-f, 8b-d, 9b, e-g, and 10; Tab. 3). Gravels are generally erosionally-based and massive, with sparse out-sized mud clasts up to 5 cm. On the other hand, sands show flat bases and are internally characterised by through- and planar-cross stratification, cross-laminations (Fig. 7d and 9d; Tab. 3). Very thin-bedded alternations of sands, silts and clays result in heterolithic bedsets up to c. 1 m-thick, in which sands can form isolated sandy ripples (Fig. 9b, 10c-f).

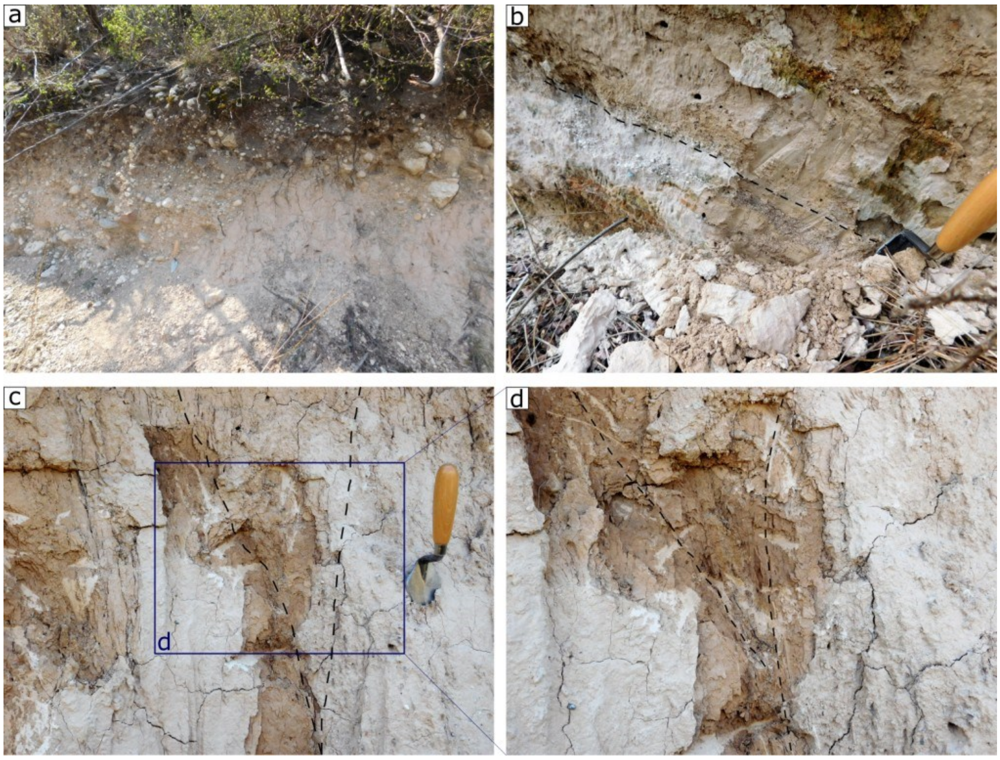


Fig. 8 - Castello outcrop, northern sector. (a) Global vision of the outcrop. Gravel scours, characterized by clast-supported massive pebbly gravel (deltaic facies association D) are highlighted by an erosional surface above glaciolacustrine facies association GL. (b) Particular showing normally graded sand (glaciolacustrine facies association GL); the dotted line highlights the inclined lamination. (c) Ice-wedge cast within mud-prone deposit (glaciolacustrine facies association GL); the dotted line evidences the cast. (d) Particular from Fig. 8c, showing vertical and high-angle inclined lamination highlighted by dotted lines.

Gravel-grade clasts are sub-angular to well rounded, with average size of 0.5 cm and max size of 5 cm. The deposit colour varies from 10YR 6/4 (light yellowish brown), 7.5YR 8/4 (pink), to 5YR 6/3 (light reddish brown), to 2.5YR 6/3 (light reddish brown). The lithological composition of the gravel fraction is well-diversified (polygenic gravel), with presence of limestone, purple rhyolites-porphyries, and quartz; among the sand-grade, limestones and purple rhyolites-porphyries clasts, mica and quartz are recognizable. Clasts are very poorly to poorly weathered.

Occurrence and interpretation: This facies association tends to form monotonous thin-bedded sections several m-thick and can be stratigraphically associated to deltaic deposits. The heterolithic structure of the deposits, in which beds with variable grain-sizes and sedimentary structures alternate, suggest deposition from numerous and discrete depositional events in a low-energy glaciolacustrine setting occasionally reached by sediment gravity flows. Silts and clays are the result of fall out deposition from suspension and may relate to homo- and hypo-pycnal flood-generated flows, originating rhytmites. Conversely, the thickest sand beds represent the product of en-masse and traction plus fall-out deposition from sediment gravity flows, most likely ignited by flood-generated hyperpycnal flows (Bennet et al., 2002; Winsemann et al., 2009, 2018; Lang et al., 2017; Fitzsimons & Howarth, 2018; Palmer et al., 2019; Sutherland et al., 2019; Kurjanski et al., 2021).

4.2. Geomorphology and spatial distribution of sedimentary facies associations

From a morphological point of view, the study area is characterized by the presence of c. 15 (moraine) ridges, constituted by glacial diamictons of Facies association G, at elevations in the range 170-215 m a.s.l. in the western flat area, and at elevations in the range 180 -305 m a.s.l. on the northern slopes of Mt La Mesa and Mt Pipalo (Fig. 3). The northern slope of Mt La Mesa is also characterized by small (kame) terraces (at elevations of 215 and 240 m a.s.l.), infilled mainly by glaciofluvial deposits of Facies association GF (Fig. 3). In this setting, Mt Rocca, Mt Castello and the slope to the North of Zuane di Sotto exposure are constituted by Mesozoic carbonates (Fig. 3). The abovementioned western flat area (172-195 m a.s.l.) is composed of at least 10 m-thick glaciofluvial deposits (Facies association GF), which are exposed along a quite continuous escarpment (northern escarpment, hereafter), extending from the Zuane di Sotto exposure to the North and the Castello outcrop to the South. Furthermore, these deposits surround the moraine ridges in the central and south-western portion of the area (Fig. 3). To the South of Rivoli Veronese town, glaciolacustrine deposits (Facies association GL) compose the flat area, adjacent to the lowermost moraine ridges of Mt La Mesa and to the West of a continuous escarpment (southern escarpment, hereafter), extending from the Mt Castello to the North to the Mt Rocca to the South (Fig. 3). Along the

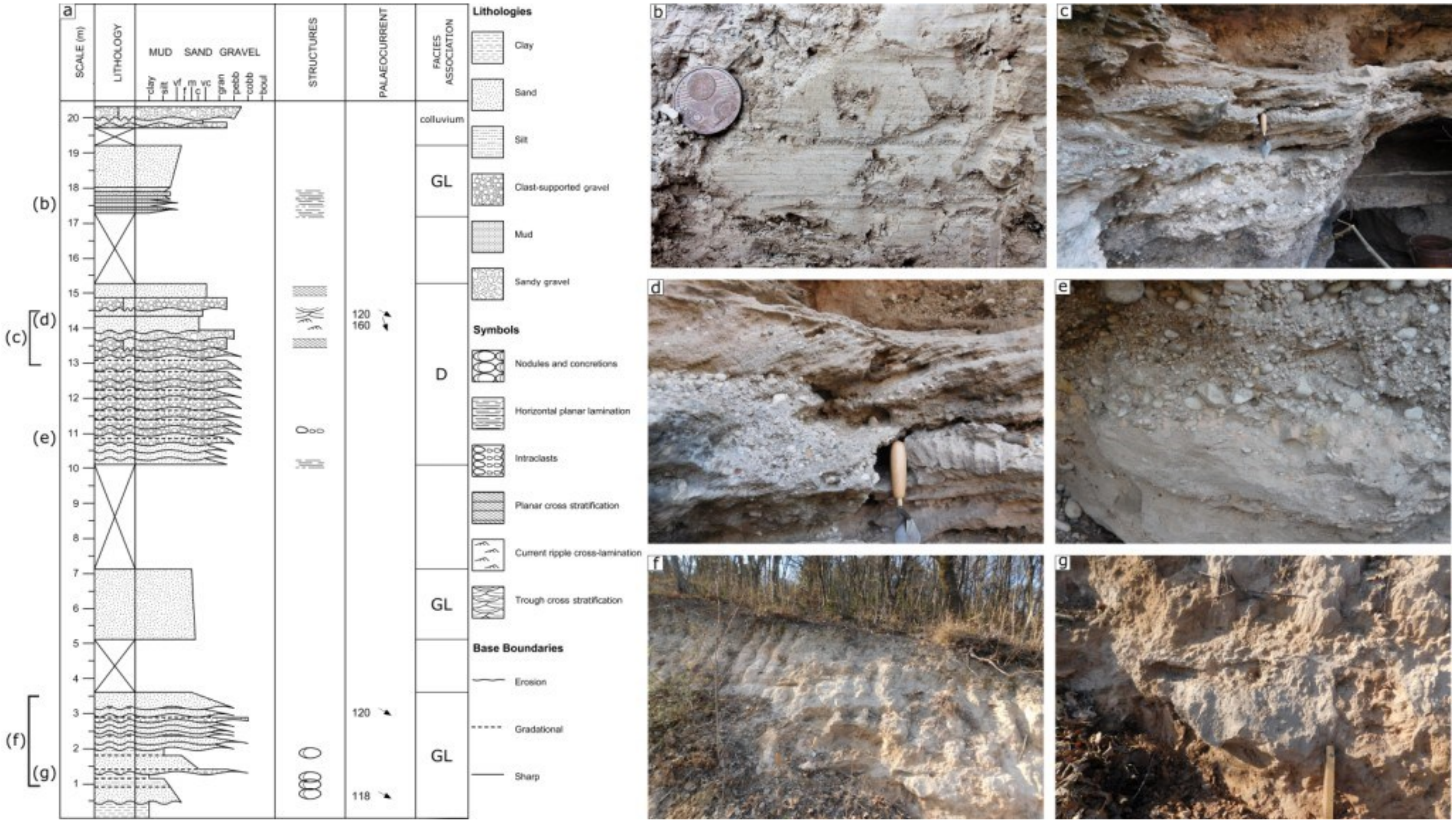
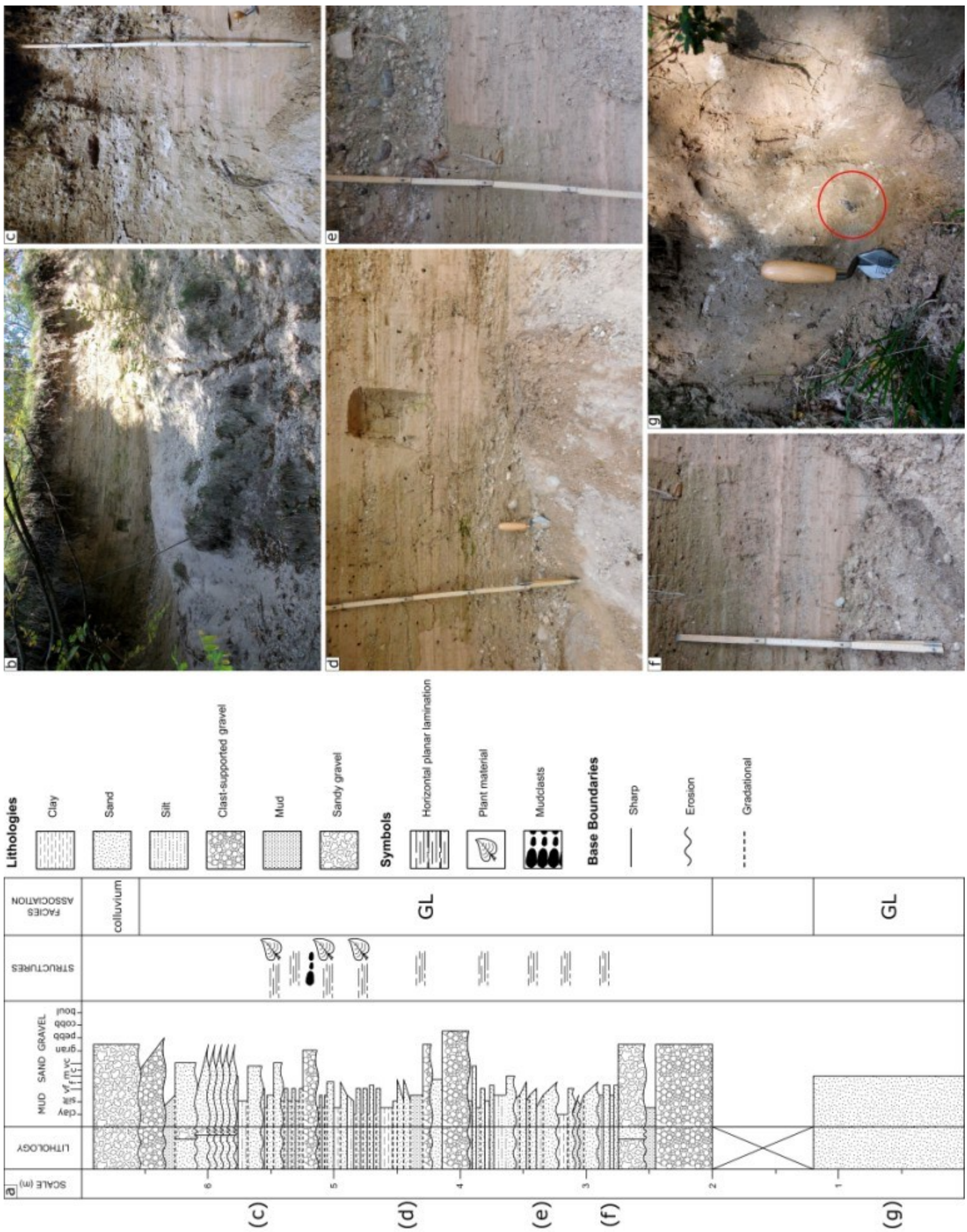


Fig. 9. - Rivoli section with the (a) stratigraphic log of the Rivoli section (drawn with Sedlog - v.3.1, Zervas et al., 2009) and the main facies associations composing it. The positions of the facies represented in b-g are displayed on the left of the stratigraphic log. (b) Rhytmites composed by horizontally laminated alternating silt, very fine sand and clay (glaciolacustrine facies association GL) at 17.60 m. (c) Cemented sand, sandy gravel and gravel with planar and trough cross-stratification (deltaic facies association D) at 13-14.50 m. (d) Particular from Fig. 9c showing the transition from trough cross-stratified gravel, to planar- and trough-cross stratified sand. (e) Particular from lower Fig. 9c highlighting the presence of numerous intraclasts at the base and within planar cross-stratified pebbly gravel. (f) Sequence of channel fills, characterized by normally graded sand to silt and gravel to very fine sand or silt (glaciolacustrine (GL) and deltaic (D) facies association) at 1-3.50 m. (g) Particular from Fig. 8f showing the channelized structures with granules and pebbles along the base of the channel.

vvvvv -- vvvvvv

Fig. 10 - Mt La Mesa section with the (a) stratigraphic log of the Mt La Mesa section (drawn with Sedlog - v.3.1, Zervas et al., 2009) and the main facies associations composing it. The positions of the facies represented in b-g are displayed on the left of the stratigraphic log. (b) Global view of the stratigraphic section. (c) Erosional surface separating rhytmites composed of silt, clay and fine and very fine sand (glaciolacustrine Facies association GL) from beds composed of normally graded sand to mud and normally graded gravel to sand (glaciolacustrine facies association GL and hyperpycnal deposit) at 5.20-6.50 m. (d) Fining upwards trend composed at the bottom by clast-supported sandy gravel with normal gradation and planar cross-stratification (hyperpycnal deposits), passing to the top at rhytimites of fine sand, silt and clay (glaciolacustrine facies association GL) at 3.90.00-5.00 m. Notice the irregularity of gravel erosional base. (e) Erosional base of the sandy gravel with evidence of planar and trough-cross stratification (hyperpycnal deposits) above finely laminated/rhytmites of sand, clay, and silt (glaciolacustrine facies association GL) at 3.30-4.00 m. (f) Fining upwards trend composed at the bottom by massive sandy gravel (hyperpycnal deposits), passing upwards towards finely laminated sand, silt and clay, normally graded fine sand, and finely laminated mud (glaciolacustrine Facies association GL) at 2.60-3.40 m. (g) Notice the pebble (marked by the red circle) inside massive silty medium sand (glaciolacustrine facies association GL) at 0.40 m.


a
b
c
d
e
f
g
SCALE (m)
LITHOLOGY
MUD SAND GRAVEL
clay
silt
vf f m c vc
gran
pebb
cobb
boul
STRUCTURES
FACIES ASSOCIATION
colluvium
GL
GL
1
2
3
4
5
6
(c)
(d)
(e)
(f)
(g)
Lithologies
Clay
Sand
Silt
Clast-supported gravel
Mud
Sandy gravel
Symbols
Horizontal planar lamination
Plant material
Mudclasts
Base Boundaries
Sharp
Erosion
Gradational

slopes connecting both the northern and southern escarpments to the present-day course of the Adige River (96 m a.s.l.), glaciolacustrine deposits (Facies association GL) outcrop. In the specific, the northern slope displays multiple terraces (with elevations varying within the range 128-155 m a.s.l.; Fig. 4). These deposits show an up to 50 m-thick overall coarsening-upward trend in the upper part of the slope and are locally intercalated by erosionally-based, coarse-grained deltaic deposits (e.g., to the East of the Napoleonic Monument; Fig. 3 and 5). At the bottom of the slope, c. 3 m of glacial diamictons of Facies association G are exposed along the deeply incised creek to the South of the Napoleonic Monument (Fig. 3). In the meanwhile, the southern slope shows a coarsening-upward trend with glaciolacustrine deposits and heteropic erosionally-based coarse-grained deltaic deposits. The deltaic facies association crops out to the South-West of Mt Rocca and more continuously from Mt Castello to the Rivoli section (Fig. 3).

4.3. Key outcrops and type stratigraphic sections

This section presents a comprehensive summary of observations made at five key-sites and type-stratigraphic sections within the investigated area. These noteworthy outcrops are listed from North to South, contributing significantly to the realization of the cross-sections of Fig. 5.

The Zuane di Sotto exposure

This exposure (Fig. 7a) is constituted by a series of relatively small outcrops straddling the northern escarpment in its north-eastern termination and located at elevations in range 170-178 m a.s.l. (Fig. 3). Proceeding from lower to higher elevations, glaciolacustrine, deltaic and glaciofluvial deposits crop out. Glaciolacustrine and deltaic deposits (Facies associations GL and D) are represented by interbedded heterolithic deposits and variously structured gravelly sands and sandy gravels, respectively (Fig. 7c). The eastern escarpment exposes c. 2 m of the glaciofluvial gravels of Facies association GF which demonstrably composes the topmost terrace (Fig. 7b). The boundary between glaciolacustrine and the glaciofluvial deposits is not exposed. However, based on morphostratigraphic relationships and observations made along the northern escarpment, we may suggest heteropic transition and coarsening upwards trend from glaciolacustrine s.l. deposits (Facies associations D and GL) towards glaciofluvial deposits of Facies association GF (Fig. 5).

The Napoleonic Monument exposure

Compared to the Zuane di Sotto, the Napoleonic Monument exposure is located in a more southern position (Fig. 3 and 5) and at lower elevations (98-128 m a.s.l.). It consists of a series of scattered small outcrops in which from lower to higher elevations, a progression from thinly-bedded and generally fine-grained glaciolacustrine deposits (Facies association GL; Fig. 7d-e) to coarse-grained and generally less-organised deltaic deposits (Facies association D) is observed. Here, the bedding of deltaic deposits locally shows inclination angles as high as c. 20° associated with evidence of soft-sediment deformations, which suggest a relatively high-gradient delta-front slope subject to gravitational deformation and slumping (Fig. 7f).

The Castello outcrop

One of the key outcrops of the northern sector is located further to the South, c. 350 m to the Northwest of Mt Castello and at an elevation of 170 m a.s.l. (Fig. 3). The Castello outcrop rests on top and to the north of a moraine ridge made of glacial diamictons belonging to Facies association G (Fig. 3). It is c. 10 m-long and exposes c. 1.5 m of deposits represented, from base to top, by glacial diamictons, trough cross-stratified sandy gravels resembling deposits of the deltaic Facies association D, and heterolithic and thinly-bedded fine-grained deposits. The latter include finely laminated sand and mud, and massive mud (Fig. 8a-b) characterized by vertical sub-millimetric to millimetric discontinuities highlighted by redoximorphic features (Fig. 8c-d) and interpretable as ice wedge casts (Cremaschi & Van Vliet-Lanoë, 1991; Shur & Zhestkova, 2003; Mariani et al., 2015).

The Rivoli section

The Rivoli stratigraphic section is exposed along the upper (between 169-189 m a.s.l.) part of a laterally extensive escarpment located immediately below the town of Rivoli Veronese (Fig. 3). The section (Fig. 9a) is c. 20.30 m-thick but partly covered and starts with thin to medium bedded alternations of muds and graded gravelly sands (Facies association GL) suggestive of deposition in a proximal glaciolacustrine environment (Fig. 9f-g). Above a partly exposed interval c. 7.5-thick, c. 5 m of planar-parallel and cross-stratified gravelly sands occur (Fig. 9c-e) interpretable as hyperpycnal deposits accumulated in a pro-delta setting (Facies association D). The section ends with a few metres of finely laminated alternations of clays, silts and very-fine sands (Fig. 9b), most likely representing a relatively distal glaciolacustrine deposit.

The Mt La Mesa section

This 6.90 m-thick section (Fig. 10a) is exposed between 185-191 m a.s.l. along a road cut at the base of the northern slope of Mt La Mesa (Fig. 3). The section is rather repetitive and overall finer-grained than the Rivoli Section. It is represented by an alternation of very thin-bedded graded sands and muds with abundant plant fragments (Fig. 10c-d). These are intercalated by rarer but thicker beds (thickness in the range 15-50 cm) of sands and sandy gravels locally rich in mud clasts (Fig. 10c-g) and can be interpreted as sediments accumulating in a glaciolacustrine environment with occasional deposition from a range of sediment gravity flow types.

4.4. Morphostratigraphic units

Based on sedimentary facies composition, spatial relationship between key sites, and geomorphological features of the morphostratigraphic unit mapped in Figure 3, this Section addresses the stratigraphic architecture of the innermost moraine ridge of the AMA. These units are coded with an acronym: the letters indicate the dominant facies association and the depositional setting (see Section 4.1 “Facies associations”), while the number denotes the glacial stage as reported in Figures 2 and 3.

Pre-Glacial Substrate

The bedrock in the area is composed by nodular limestone, well-bedded marly limestone and oolitic limestone, reported as undistinguished Mesozoic limestones (unit C) in Figure 3. The substrate crops out to the North of the Zuane di Sotto exposure and on most of Mt Castello; to the South, limestones crop out to the North of Mt Pipalo and constitutes Mt Rocca (Fig. 3). Limestones are eroded and covered by most successive units. This bedrock is reported in literature by Venzo (1961) as "Cretaceous and Pre-Cretaceous series", with references to Cozzaglio (1934); Venzo et al. (1969) attributed the sedimentary succession as Bajocian-Lower Tithonian in age.

Glacial Advance 1

This unit consists of Glacial diamicton (unit G1) (Fig. 3). These deposits compose the tills of the moraine ridges in the Mt Pipalo area, at the southernmost point of the investigated area. Compared to younger glacial units (see Section 4.4.3 and Section 4.4.4), ridges belonging to this unit are comparatively less continuous and more external (Fig. 2 and 3). The upper boundary is the current topography and is characterized by a 50 cm thick 10YR to 7.5YR soil, or alternatively by an erosional surface from Post-Glacial, Glacial Retreat and Glacial Advance 2 units. The clasts are not weathered but most of its deposits are characterised by thin and discontinuous calcretes and $CaCO_3$ nodules. The lower boundary is not exposed; however, based on morphostratigraphic interpretations we hypothesise an erosional surface above the Pre-Glacial Substrate. This unit corresponds to previously attributed: Würm I and Riss gravel moraines (Venzo, 1961); Riss gravel moraines (Venzo et al., 1969); diamicton from Solferino Moraine Stage - Late Pleistocene (Cremaschi, 1987); moraine ridges of the greatest glacial expansion from M.te Police unit - Upper Pleistocene (Accorsi et al., 1990); glacial ridges of the LGM (Ravazzi et al., 2014).

Glacial Advance 2

This unit consists of Glacial diamicton (unit G2) (Fig. 3). These deposits compose the tills of the moraine ridges on the northern flank of Mt La Mesa and at its top, in the southern portion of the investigated area. This unit differs from the other glacial phases by higher and more continuous ridges, and sometimes doubling ridges (Fig. 2 and 3). The upper boundary is the current topography and is characterized by a 50 cm thick 10YR to 7.5YR soil, or alternatively by an erosional surface from Post-Glacial and Glacial Retreat units. The clasts are not weathered but most of its deposits are characterised by thin calcretes and $CaCO_3$ coatings on clasts. The lower boundary is an erosional surface on the Pre-Glacial Substrate and on Glacial Advance 1 deposits (Accorsi et al., 1990). This unit corresponds to previously attributed: Würm I and Würm II gravel moraines (Venzo, 1961); Riss gravel moraines (Venzo et al., 1969); diamicton from Solferino Moraine Stage - Late Pleistocene (Cremaschi, 1987); moraine ridges related to the retreat of the Adige-Sarca glacial system from the Fiffaro unit - Upper Pleistocene (Accorsi et al., 1990); glacial ridges of the LGM (Ravazzi et al., 2014).

4.4.1. Glacial Retreat

This unit consists of Glaciofluvial gravels and sandy gravels (unit GF3), Deltaic sandy gravels (unit D3), Glaciolacustrine heterolitic deposits (unit GL3), and Glacial diamicton (unit G3) (Fig. 3). Unit G3 glacial diamicton compose the tills of the moraine ridges surrounding Zuane to the North and to the West, the ridges to the West of Mt Castello and Rivoli Veronese town, and the ones at the base of the northern flank of Mt La Mesa (Fig. 3). Unit G3 glacial diamicton are overlaid/juxtaposed and partially eroded by units GF3, D3, and GL3 (glaciofluvial, deltaic and glaciolacustrine deposits). Glaciolacustrine deposits (unit GL3) overlay unit G3 glacial diamicton, and are composed by sand, silt and clay representing a proglacial lake system (see Section 4.1.4). Unit GL3 outcrops along both northern (between the Adige River, Zuane and Mt Castello) and southern (between Mt Castello, Rivoli Veronese and Mt La Mesa) slopes. Along the slopes, heteropic deltaic sandy gravels of unit D3 crops out near the Napoleonic Monument location, along the escarpment below the Rivoli Veronese town, and to the South-West of Mt Rocca. To the South, unit GF3 glaciofluvial gravels compose the infilling of small kame terraces (length is c. 150-180 m) along the northern flank of Mt La Mesa, and dominate the western portion of the investigated area as an outwash proglacial system, which erodes all the other deposits and units.

This morphostratigraphic unit differs from the other glacial ones by its inner position, highlighted by the concentric and discontinuous moraine ridges. The upper boundary is the current topography and is characterized by a 50 cm thick 10YR to 7.5YR soil horizon, or sometimes by the erosional surface of the Post-Glacial unit. Clasts are not weathered but some deposits are characterised by thin calcretes. The lower boundary with other units is an erosional surface. This unit corresponds to previously attributed: Würm II and Würm III gravel moraines, Würm II glaciofluvial coarse gravels and Würm III fluvio-lacustrine deposits (Venzo, 1961); Riss and Würm gravel moraines, Riss I and Riss II glaciofluvial gravels, Würm-Riss Interglacial fluviolacustrine deposits (Venzo et al., 1969); diamicton from Solferino Moraine Stage - Late Pleistocene (Cremaschi, 1987); moraine ridges related to the retreat of the Adige Glacier (Fiffaro unit - Upper Pleistocene), kame terraces and glaciofluvial deposits related to the retreat of the Adige Glacier (Zuane unit - Upper Pleistocene), glaciolacustrine deposits of the Rivoli Veronese town and deposits of the Late Glacial paleochannel of the Adige River (Rivoli unit - Late Glacial) (Accorsi et al., 1990); glacial ridges of the LGM (Ravazzi et al., 2014).

4.4.2. Post-Glacial

This unit consists of Alluvial deposits (unit A) and Slope deposits (unit S) (Fig. 3). Unit A deposits are composed of silt, sand and gravel, which presence is limited to the banks and terraces on the current course of the Adige River. Unit S deposits are formed by colluvium and slope debris and derive from the dismantling of previous glacial, glaciofluvial and substrate deposits. The lower boundary with other units is always an erosional surface. The upper boundary is the current topography and is characterized either by the absence of soil cover or by a 10YR to 5YR soil up to 50 cm thick.

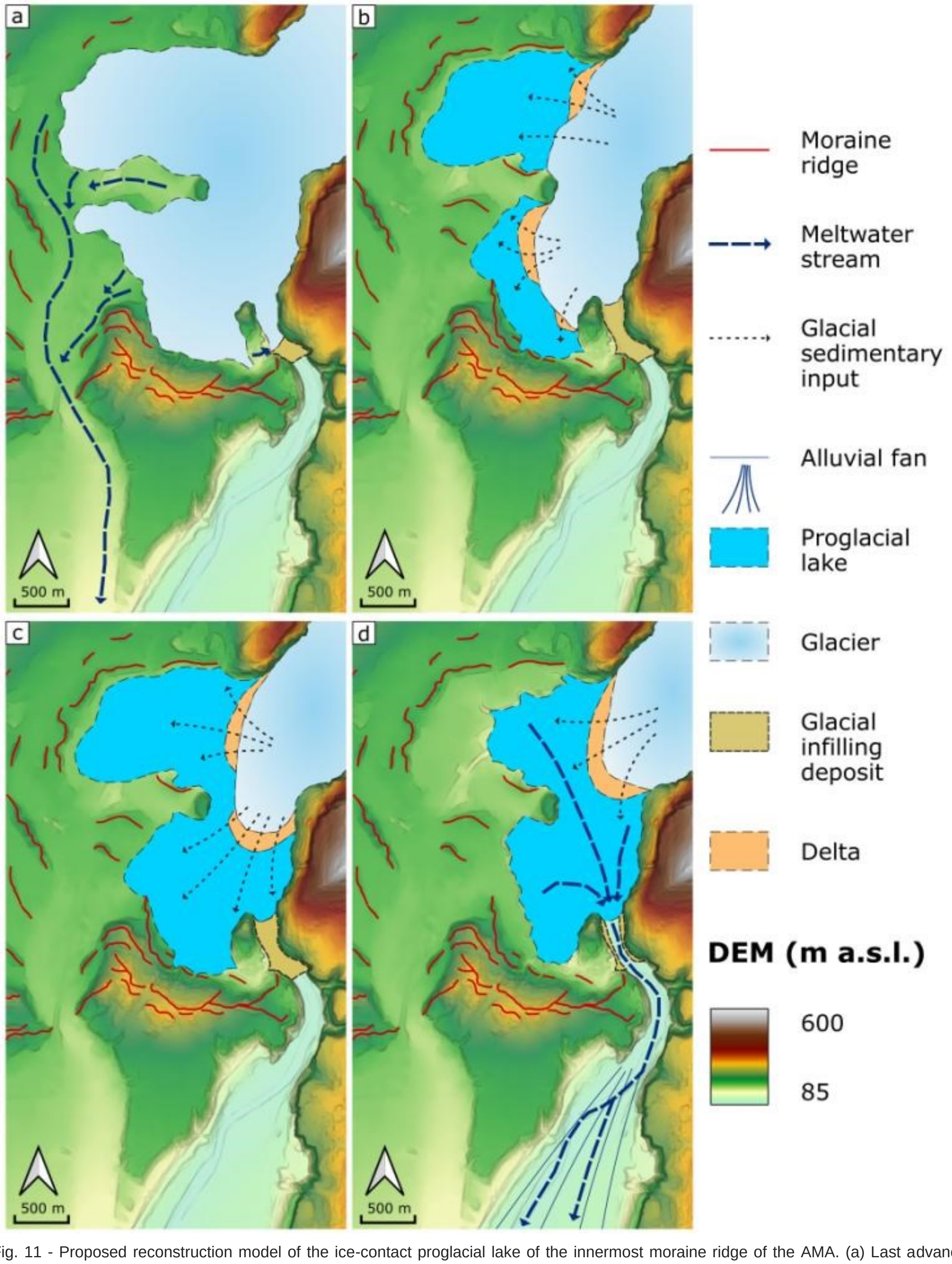


Fig. 11 - Proposed reconstruction model of the ice-contact proglacial lake of the innermost moraine ridge of the AMA. (a) Last advance stadial phase with moraine ridge build-up and meltwater streams passing through the moraine ridges. (b) Onset of the proglacial lakes. Here the lake is split by the bedrock of Mt. Castello. (c) Coalescence of the two lakes due to the progressive glacial retreat. (d) Final GLOF of the proglacial lake generated by the breakthrough in the sedimentary plug.

5. DISCUSSION: BASIN-FILL ARCHITECTURE AND EVOLUTION OF THE AMA INNERMOST MORAINE RIDGE

Morphostratigraphic investigations show different types of facies associations occurring in the study area that can be attributed to different units of Late Pleistocene (glacial, glaciofluvial, glaciolacustrine) and Holocene (related to fluvial or pediment systems) deposits (Fig. 3). Furthermore, field survey indicates that two different glacial advances occurred in the area, followed by a glacial retreat. Notably, these phases are marked by tills forming moraine ridges and double ridges. This context implies a complex glacial history occurred in the LGM and pedogenesis affecting deposits only during the Holocene (Accorsi et al., 1990). The age attributions are based on morphostratigraphic markers and correlations made according to literature (Cremaschi, 1987; Accorsi et al., 1990; Bini & Zuccoli, 2004; Bini, 2012; Monegato et al., 2017) due to the lack of absolute dating.

Once the Adige glacier retreated behind the innermost moraine ridges (Fig. 11a), meltwater infilled the depression, also thanks to the low permeability of the underlying tills (Anderson, 1989; Bersezio et al., 1999; Fig. 11b). Two different interpretative models can explain such setting: 1) a kame terracing sequence, with a series of younger downscaling terraces during glacial retreat; 2) the infilling of the AMA innermost moraine ridge by one or more proglacial lake systems. We propose the glaciolacustrine hypothesis. The morphostratigraphic approach suggests that such proglacial lakes were a continuum between an ice-contact proglacial lake and a glaciolacustrine delta system (Fig. 11b-c); furthermore, the proglacial lakes were dammed by moraine ridges and other glacial deposits, as well as by the glacier itself. Such barriers also occluded the pre-existing Adige Canyon, thus constraining the meltwater drainage pathways of the Adige Glacier to move West, cutting down the moraine ridges during both glacial advances and retreat (Fig. 1, 2 and 11).

Along the innermost moraine ridges of the AMA, the glaciolacustrine succession is almost continuous, occasionally interrupted by deltaic sandy gravels. These intercalations may be related to more continuous and sustained hyperpycnal flows or to aggradation and backstepping of delta systems. The northern slope, comprised between Zuane di Sotto exposure to the North and Mt Castello outcrop to the South, shows a general coarsening-upward trend from mud-prone to sandy deposits, suggesting a transition from distal to proximal glaciolacustrine sedimentation. Whereas along the southern slope, comprised between Mt Castello to the North and Mt La Mesa to the South, glaciolacustrine sediments show a coarsening upwards trend, with alternating mud-prone and sandy deposits heteropic to deltaic facies association. In this context, the presence of coarser-grained deposits in the Rivoli section can attest to a proximal/deltaic setting respect to the finer-grained sediments of the Mt La Mesa section, which can testify distal glaciolacustrine environment.

Studied sections and facies associations show that proglacial lakes included delta systems, transitioning laterally to direct contact of the ablating ice-front to the proglacial lake (Fig. 11). In this context, the glaciolacustrine setting is characterized by shifting from deltaic system to proximal and distal glaciolacustrine depositional environments. Delta systems show great mobility in their sedimentary distributary pattern, with erosionally-based gravelly deltaic heteropic to sandy and mud-prone glaciolacustrine deposits. This reflects how the proglacial lake depositional style is dominated by a series of gravity flows driven processes, such as debris flows, hyperconcentrated and concentrated density flows, high- and low-density turbidity currents, slumping, up to fall out settling, but also related to fluvial processes with tractive currents and hyperpycnal flows (i.e., Bersezio et al., 1999; Bennet et al., 2002; Winsemann et al., 2009; Lang et al., 2017, 2021; Palmer et al., 2019). These depositional processes may have an episodic to quasi-steady nature led by different trigger mechanisms, from remobilisation of sediments to sustained flows of turbidity currents originated by meltwater and deltaic input, to currents generated by more or less continuous river floods (i.e., hyperpycnite). Erosional activity is recorded by scours, intraclasts, and gravelly erosional bases (Bennet et al., 2000, 2002); although they may correspond to water level fluctuations, no basin-wide unconformity was recognised. In this setting, the potential water depths is not very high with maximum water depth circa 25-50 m. The infilling of the basin is also a matter of discussion, since there is no incontestable evidence of a single cycle of basin-fill before the final lake drainage happened during glacial retreat. While we do not exclude a priori the possibility of multiple cycles of basin-fill, the absence of recognizable lake-wide unconformities suggests a single cycle model (i.e., Bennet et al., 2002).

The rapid variations of the depositional environments can be related to different factors, such as the available accommodation space, the fluctuations of the glacier front, the sedimentary input pathways (delta vs ice-front), and the quantity of water vs sediments discharge (i.e., Bennet et al., 2000, 2002; Winsemann et al., 2018; Palmer et al., 2019). All these factors can change between the northern and southern branches, which show great affinity but also some divergences. Among them, the different stacking of facies associations suggests the plausible development of two separated lacustrine branches during part or all of the final stage of glacial retreat, possibly coalesced together (Fig. 11b-c). Frost action, recorded by the occasional presence of ice-wedge casts formed into glaciolacustrine sediments (Fig. 8), was also effective during the glacial retreat phase at the end of LGM as well as during previous periods (Cremaschi & Van Vliet-Lanoë, 1991; Mariani et al., 2015). These casts show the occurrence of freeze-thaw cycles at the surface of the deposits and mark clear evidence of seasonal permafrost formation in a periglacial environment after the desiccation of proglacial lakes. The presence of redoximorphic features inside the casts can indicate successive water saturation processes possibly related to a warmer climate phase (i.e., Cremaschi, 1990; Cremaschi & Van Vliet-Lanoë, 1991; Shur & Zhestkova, 2003; Mariani et al., 2015).

In the final retreat of the Adige Glacier the proglacial lake disappeared (Fig. 11d). This can possibly relate to the reopening of the Adige Canyon. In fact, we postulate that the canyon was already incised before the LGM, considering the tectonic, seismic activity, and subsidence movements that characterized both the Venetian Plain and Lower Adige Valley since the Pliocene up to the Middle Pleistocene, and still seismically active in historical times (Sorbini et al., 1984; Scardia et al., 2015; Martin et al., 2020). The Adige Canyon (Fig. 2) is a small passageway bordered by very steep limestone walls and a meander geometry: the formation of such incision must have required an erosional work much longer than the post-deglaciation time-window. Since the canyon threshold is significantly lower than the AMA level, meltwater would have preferentially passed in it instead of eroding the AMA moraine ridges, making it implausible to forming proglacial lake inside the AMA and meltwater pathways between the two moraine amphitheatres. The obstruction of the canyon is confirmed by the presence of notches (inland karst notches, Shtober-Zisu et al., 2015) on the walls in the passageway and of glacigenic sediments on both sides of the canyon. Furthermore, another portion of the Adige River path is incised in the bedrock between Parona and Verona (Fig. 1; Dal Piaz et al., 1968; Venzo et al., 1969; Sorbini et al., 1984). Furthermore, the canyon obstruction is corroborated by the morphology of the AMA, which shows how the LGM meltwater pathways from the Adige Glacier flowed towards the West, cutting moraine ridges and bending South in the lowlands between the Garda and Adige Glacial Amphitheatres (Fig. 1 and 11; Venzo, 1961; Venzo et al., 1969; Cremaschi, 1987). This condition would have lasted until the final recessional phase, when the Adige River finally managed to break the sedimentary plug and started to flow through the canyon, as is the current river setting (Fig. 11d). The presence of glacial deposits filling most of the canyon is supported by the occurrence of boulders in the LGM Adige glaciofluvial fan sedimentary succession near the city of Verona, c. 20 km South the AMA and 15 km East the maximum glacial expansion of the Adige-Sarca glacier (Cozzaglio, 1933; Sorbini et al., 1984). In fact, during the LGM glacial tongues did not reach the area of Verona, making the occurrence of these megaclasts (named in literature “erratics” or “glacial erratics”) only possible through transportation by high-concentrated floods. Considering these points, we propose that the opening of the Adige Canyon was a sudden, dramatic event, likely a glacial lake outburst flood (GLOF; Fig. 11d). The GLOF could have been triggered by a landslide of glacial sediments and/or ice in the ice-contact lake or by a huge and rapid high-density meltwater discharge from the proglacial lake. GLOFs have been reported from numerous locations in other sectors of the Venetian and Friulan Plain (Northern Italy) and they are also common in other glaciated areas of the world (i.e., Desio & Orombelli, 1983; Hewitt, 2009; Monegato et al., 2020; Panin et al., 2020; Emmer, 2023). In such perspective, the sedimentary process in charge of the placement of the ‘Verona Erratics’ is more similar to the one proposed by Desio & Orombelli (1983) to interpret the origin of the ‘Punjab Erratics’. Furthermore, the drainage of the proglacial lake generated a fluvial erosional surface, composed by erosional river terraces and channel (i.e., Bennet et al., 2000, 2002; Panin et al., 2020).

6. CONCLUSIONS

The mapping and sedimentary facies analysis of the innermost moraine ridge of the AMA gives a complex insight on the Adige Glacier evolution during the LGM and the critical phase of the last deglaciation, regionally dated between 24 and 17 ka (Fontana et al., 2014; Ravazzi et al., 2014; Wirsig et al., 2016; Monegato et al., 2017; Braakhekke et al., 2020). In our study we could assess that:

- The main and outermost moraine ridges of the AMA were built during at least two glacial advances, while the inner ones during a glacial retreat. In the absence of absolute ages, morphostratigraphy suggests that these advances can be correlated to LGM multi-fold advances (i.e., Monegato & Ravazzi, 2018).
- Landscape evidence, morphostratigraphy and depositional architecture from the sedimentary facies associations of the AMA innermost moraine ridge indicate that this area was occupied by a two branching proglacial lake, dammed by moraine ridges and glacial deposits as well as by the glacial front.
- The basin-fill of the proglacial lakes shows that this setting can be interpreted as a continuum between an ice-contact proglacial lake and a glaciolacustrine delta system, with many vertically and laterally shifts of facies associations.
- The reconstruction of the drainage of the proglacial lakes leads to a GLOF hypothesis related to the reopening of the Adige Canyon. This is supported by the presence of boulders (“erratics”) along the LGM Adige glaciofluvial fans (Cozzaglio, 1933; Sorbini et al., 1984) and by the formation of a fluvial erosional surface in the innermost moraine ridge of the AMA. This model is in accordance with similar dynamics from other Southern Alpine contexts (i.e., Fontana et al., 2014; Monegato et al., 2020) and adds a key piece in the transition from the LGM to the deglaciation in the region.

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