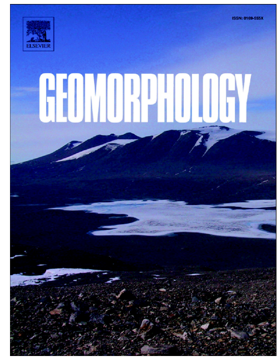

Discovery and dating of Pre-LGM deposits in a high catchment of the Dolomites (Italy): New insights on climate-related geomorphological processes during the Late Pleistocene

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Discovery and dating of Pre-LGM deposits in a high catchment of the Dolomites (Italy): new insights on climate-related geomorphological processes during the Late Pleistocene

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Abstract

The results from the analysis of a relatively deep stratigraphic sequence from a formerly glaciated plateau in the Upper Badia valley (Dolomites, Italy) are discussed, and the first insight on Late Pleistocene sedimentary records and geomorphological evolution of the area are provided. The investigated sequence comprises: i) cohesive sediments interpreted as colluvial-eluvial in origin or as stagnant water deposits; ii) sandy diamicton and dolostone monolithic sediments interpreted as gravity-induced deposits, possibly owing to debris flows or wash out/reworking of rock avalanche deposits from the surrounding dolomite ridges; iii) silty diamicton interpreted as lodgement till, possibly attributed to the Last Glacial Maximum (LGM). Radiocarbon dating results and interpretation of stratigraphic data, supported by geomorphological field surveys, remote sensing data analyses and palaeo-climatic and palaeo-environmental data from literature, enabled us to conclude that the investigated plateau (Pralongià, ca. 2000 m a.s.l.) was likely ice-free for most of Marine Isotope Stage 3. In particular, between 38 ka BP and the inset of full-glacial conditions (LGM ~27 ka BP) clastic gravity-induced sediments were deposited within the study site. Supraglacial transport is supposed to have played a role in the emplacement of gravity-induced deposits from the surrounding dolomite cliffs to the plateau. This study resulted in the first Pre-LGM record of sedimentation and palaeo-environmental conditions inside the Eastern Dolomites in the 46 to 38 ka BP period.

Key words: high mountain geomorphology; climate change; radiocarbon dating; MIS 3; Dolomites

Highlights

- The Dolomites' plateau investigated was ice-free at some 46-38 ka BP
- At ca. 38-27 ka BP gravity-induced deposits were emplaced on the plateau
- Allochthonous gravity-induced deposits reached the plateau thanks to an ice bridge

1. Introduction

The last glacial cycle was characterised by millennial scale climate changes, which provide information on how fast and abruptly climate can change. Improvement of knowledge on spatial and temporal features of past rapid climate changes is a fundamental key for understanding their effects on landscape and providing data for climate modelling. In particular, understanding the response of the landscape to past climate conditions, such as those occurring during the last glacial cycle, is crucial for inferring present and future landscape responses to the ongoing climate change in the Alps (Reynard et al., 2012).

The Last Glacial Maximum (LGM, cf. CLIMAP, 1976), comprised within Marine Isotopic Stage 2 (MIS 2, 29-11 ka BP), was the period in which Alpine glaciers reached their maximum advance during the last glacial cycle (Ivy Ochs, 2015 and references therein). In most cases, this dramatic glacial advance obliterated Pre-LGM geomorphological and stratigraphic records, especially in high Alpine catchments.

The period preceding the LGM and corresponding to Marine Isotopic Stage 3 (MIS 3, 60-29 ka BP) is known as a period of great climate variability (Rabassa and Ponce, 2016) with cyclic and frequent alternation of colder stadials and warmer interstadials. Considering the $\delta^{18}O$ curve from Greenland ice core records, it can be deduced that glaciers must have been more extensive than today, although less extensive than during the LGM. Data on MIS 3 environmental and climatic conditions in central and southern Europe are not that many, especially those relevant to high-altitude areas.

The considerable climate variability of MIS 3 is recorded by e.g. speleothems and lacustrine and loess deposits in the Northern Alps and their foreland (Starnberger et al., 2013 and references therein). Less is known about the southern side. Only a few papers providing Late Pleistocene palaeo-environmental and palaeo-climate information on the southern Alpine foreland are available in literature (e.g. Pini et al., 2010; Carrera et al., 2018).

Within this context, this study provides further insights, from a high-Alpine perspective, on palaeo-environmental and palaeo-climate conditions occurring during MIS 3 in the Eastern Dolomites (Southern Alps, Italy). For this purpose, the paper discusses the results from the analysis of a relatively thick stratigraphic sequence, possible due to excavation works and drilling surveys on a formerly glaciated plateau, the Pralongià in the Upper Badia (Alta Badia) valley. They revealed deposits older than the LGM and allow to extend the morphostratigraphic record beyond MIS 2. Reconstruction of the environmental and landscape evolution in the study area and its surroundings was previously limited to studies concerning the relationships between past climate changes and slope instability processes, which have happened since the retreat of the LGM ice mass (Soldati et al., 2004, 2006; Borgatti and Soldati, 2010). Reconstruction was also based on stratigraphic and palynological studies on lacustrine and peat bog sediments of the last 13,000 years BP (Soldati et al., 1997, 2006; Corsini et al., 2001; Poto et al., 2013). A recent research was devoted to the reconstruction of glaciers' fluctuations in the southeastern sector of the Alta Badia valley (Ghinoi and Soldati, 2017).

2. The study area

The study area is located within the Alta Badia valley and corresponds to the isolated Pralongià plateau in the Eastern Dolomites (Autonomous Province of Bolzano, Italy, Fig. 1). The area exceeds 2000 m in elevation and is surrounded by high dolomite peaks up to 3000 m high (Soldati, 2009).

The rock types outcropping in the Pralongià plateau are alternations of marls, marly limestones and calcarenites, ranging in age from Middle to Upper Triassic and belonging to the S. Cassiano and Wengen Formations (Panizza et al., 2011). On the western side of the plateau, hyaloclastites of the Upper Cretaceous (pillow and block lavas, volcano-clastic sandstones) belonging to the Fernazza Group also crop out.

The Wengen Formation (Middle Triassic) is a thick basinal sequence made up of volcano-clastic sediments including alternations of sandstones with clays and marls. The S. Cassiano Formation (Middle-Upper Triassic) is a turbidite sequence, with alternations of grey-brown marls and marly limestones, calcarenites and breccias. The Wengen Formation crops out in the northern part of the Pralongià plateau, while the S. Cassiano Formation is found in the southern one.

The Pralongià plateau is bounded by deep valleys and surrounded by towering dolomite ridges (Gardenaccia, Setsas, Conturines) almost exclusively made up of massive or stratified dolostones from Mid-Upper Triassic (Dolomia Cassiana and Dolomia Principale) and secondarily by Jurassic limestones ascribed to Rosso Ammonitico Formation and Calcari Grigi Group, which build the highest peaks.

The Pralongià plateau bears evidence of past presence of glaciers. In fact, the plateau hosts scattered glacial deposits – including (exotic) clasts of different rock types which do not crop out in the study area (e.g. Rosso Ammonitico and phyllite pebbles) – ascribed to the LGM based on detailed geomorphological field surveys (Panizza et al., 2011; Marchetti et al., 2017). Scattered dolostone blocks – from metre to sub-metre, rounded to sub-rounded – can be found on the plateau. They testify to significant glacial transport considering that dolostone outcrops are located at around 4 km of distance to the plateau and deep valleys stand in between (Panizza et al., 2011).

Considerable slope movements have affected the Pralongià plateau since the retreat of the LGM glaciers. They are mainly of earth-slide/earth-flow type, affecting the marly and clayey rocks of the Wengen and S. Cassiano Formations. The largest landslide is the Corvara landslide, which is still active today (Corsini et al., 1999, 2005; Panizza et al., 2011). Glacial debuttressing, permafrost melting and high relief energy have favoured the occurrence of slope instability processes also in the jointed dolomite masiffs/cliffs surrounding the Pralongià plateau. These movements are mainly rock falls and rock slides which, in some cases, attained a considerable extension (Panizza et al., 2011).

Previous studies do not report about subsurface deposits, which were recently observed in drillings carried out on the Pralongià plateau. They consist of dolomite debris of problematic interpretation (due to textural and stratigraphic issues) whose genetic interpretation will be discussed further on (cf. sections 5 and 6) based also on ^{14}C dating.

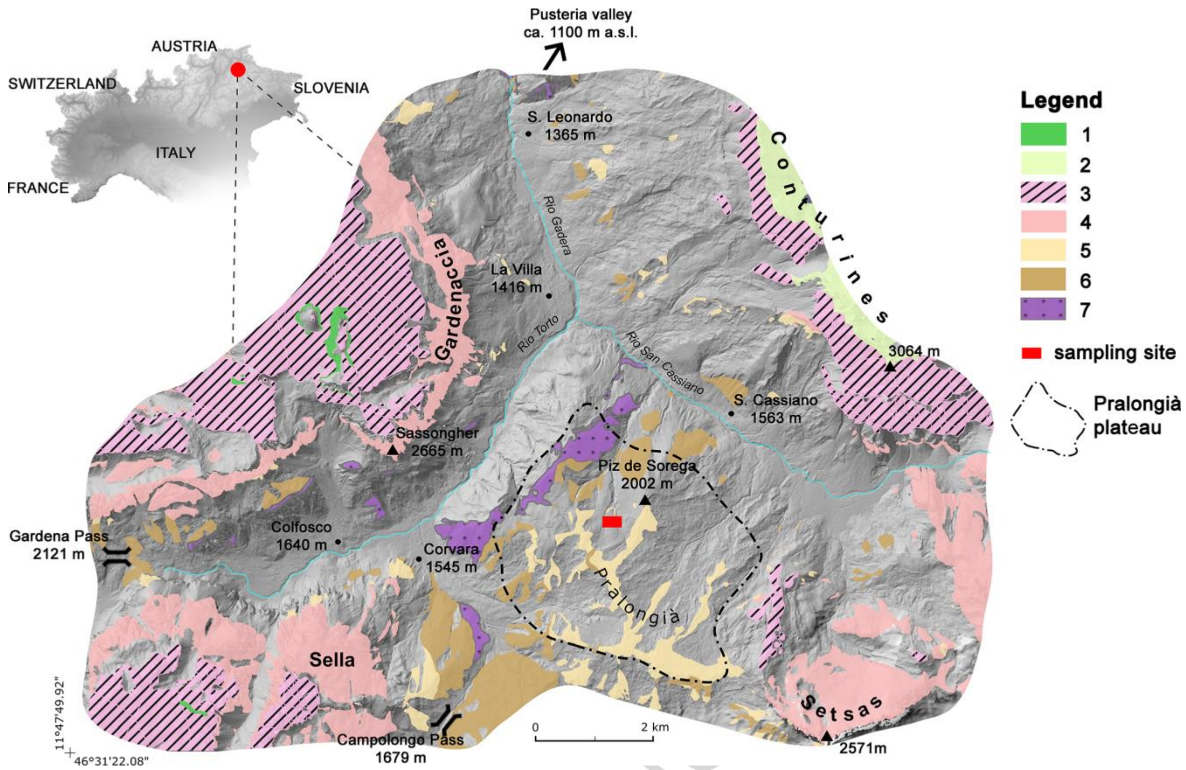

Fig. 1. Location of the study area and main bedrock outcrops (modified after Marchetti et al., 2017). 1) Rosso Ammonitico; 2) Calcari Grigi Group; 3) Dolomia Principale; 4) Dolomia Cassiana; 5) S. Cassiano Formation; 6) Wengen Formation; 7) hyaloclastites (LiDAR data courtesy of Servizio cartografia provinciale e coordinamento geodati, Autonomous Province of Bolzano). Quaternary deposits correspond to non-coloured areas.

3. Glacial fluctuations in the Alta Badia valley since the LGM

In the Alta Badia valley, evidence of past glacier fluctuations is found in the widespread glacial deposits, which previous authors attributed to the LGM and to the Lateglacial period (Fig. 2). According to literature, during the LGM an extensive glacial tongue coming from the north covered the Alta Badia valley, whilst during the Lateglacial only local valley glaciers developed.

Penck and Brückner (1909) inferred that the primary feeding area of the main glacier was from the Pusteria valley, located to the NE (Fig. 2). The glacial tongue might have had an upward movement within the valley – opposite to the present water-flow direction – and reached some 2300 m in altitude. This hypothesis was based on the finding of erratic crystalline boulders close to the S. Leonardo and S. Cassiano villages; their provenance was identified from the Pusteria valley, where crystalline rocks do crop out.

Mutschlechner (1933), who recognised and mapped widespread LGM glacial deposits above the Pralongià plateau, followed Penck and Brückner's hypothesis. In addition, he identified the presence in the area of erratic dolostone boulders which, he assumed, originated from the Setsas massif.

If we consider a LGM glacial surface at an altitude of 2300 m all over the Alta Badia valley, then an ice cap some 100-200 m thick (Castiglioni, 1940; Bruschi et al., 2009) might have covered the Pralongià plateau. As previously mentioned, scattered erratic boulders of dolostone can be found on its top. Among LGM landforms, worthy of note are the two moraine ridges located at the base of the north-western side of the Conturines massif, east of the village of S. Leonardo (Panizza et al., 2011; Marchetti et al., 2017).

The Lateglacial is marked by the relatively quick disappearance of the LGM ice cap, substituted by local valley glaciers following an opposite flow direction with respect to the LGM ice mass and departing from the highest Dolomite plateaus surrounding the valley (Marchetti et al., 2017). Valley glaciers were responsible for the deposition of frontal and lateral moraines, as reported by Castiglioni (1964) who mapped frontal moraine ridges attributed to the Bühl (Sciliar) stadial along the Gadera stream between La Villa and S. Leonardo (Ghinoi and Soldati, 2017). These moraine remains witness the presence in the area of a local valley glacier moving toward the north. Lateglacial frontal and lateral moraines can be identified, particularly in the southeastern sector of the Alta Badia within the S. Cassiano valley, although they were partly obliterated by erosional and gravity-induced slope processes. It should be noticed that evidence was found that the upper part of the Pralongià plateau was already ice-free during the Lateglacial. This is witnessed by the dating of a charcoal sample taken from an excavation made close to Piz Sorega, at an elevation of 1937 m, which was dated back to ca. 16,000 cal years BP (Panizza et al., 2011).

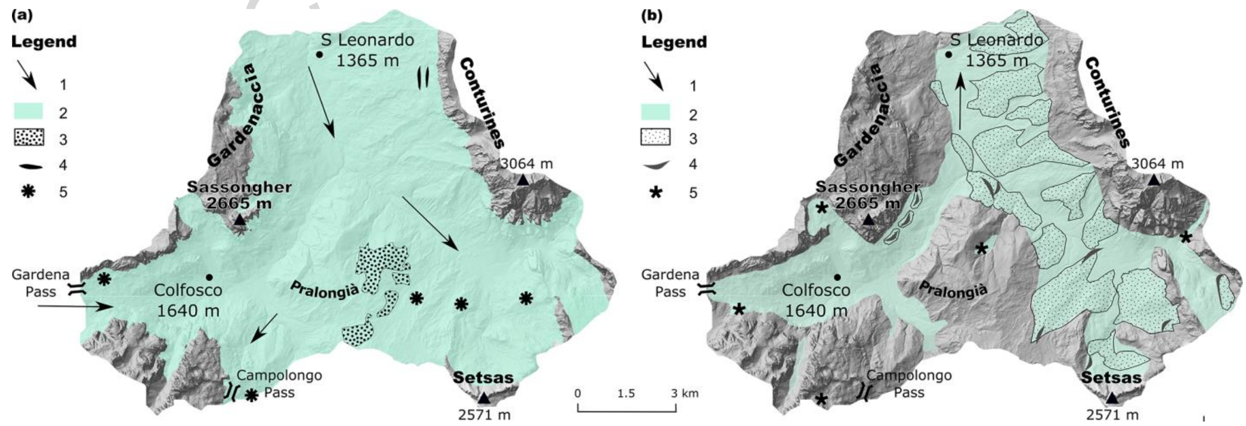

Fig. 2. Glacial features in the Alta Badia valley (modified after Marchetti et al., 2017). (a) Extent of glaciers during the LGM, inferred by assuming a glacial surface at 2300 m a.s.l.: 1) flow direction of the LGM ice

masses; 2) LGM ice cover extent; 3) LGM glacial deposit; 4) LGM moraine ridge; 5) unmappable glacial deposit (LGM). (b) Extent of early Lateglacial ice mass inferred from maximum elevation of Lateglacial deposits: 1) flow direction of the early Lateglacial ice mass 2) early Lateglacial ice mass; 3) glacial deposit (Lateglacial); 4) Lateglacial moraine ridge; 5) unmappable glacial deposit (Lateglacial). LiDAR data courtesy of Servizio cartografia provinciale e coordinamento geodati, Autonomous Province of Bolzano.

4. Materials and Methods

This study is focused on the analysis of stratigraphic data from cores collected by means of eight continuous-coring boreholes, ranging in depth from 15 to 25 metres, carried out during drilling surveys for the construction of a water-retention basin. The eight boreholes were located west of the Ciampai Hut, on the Pralongià plateau, at an altitude of ca. 1910 m to 1930 m (Fig. 3). The stratigraphic analysis of cores was supported by observations made in correspondence of excavation fronts exposed during the basin construction. Within the eight cores (Figs. 3 and 4), we recognised different sediment types to which a genetic interpretation was attributed, as shown in Table 1.

A total of six samples of bulk organic sediment, essentially dark coloured silt, were collected and radiocarbon dated: five samples from three of the eight cores and one sample from an excavation wall (Fig. 5), the latter located close to BS8-P core. Samples were prepared and analysed at Beta Analytic Inc. laboratories (Florida) using Accelerator Mass Spectrometry (AMS). Ages were calibrated by Beta Analytic using IntCal13 database (Reimer et al., 2013) according to Talma and Vogel (1993). Calibrated ages are reported with two sigma (95% of confidence).

Detailed geomorphological field surveys were carried out and remote sensing data (a 1.5x1.5 m resolution LiDAR Digital Elevation Model, courtesy of the Autonomous Province of Bolzano, orthophotographs from the Italian Ministry for Agricultural Policy – AGEA – taken in 2014, Google-Earth images) were analysed in order to frame the location of the boreholes in a geomorphological context.

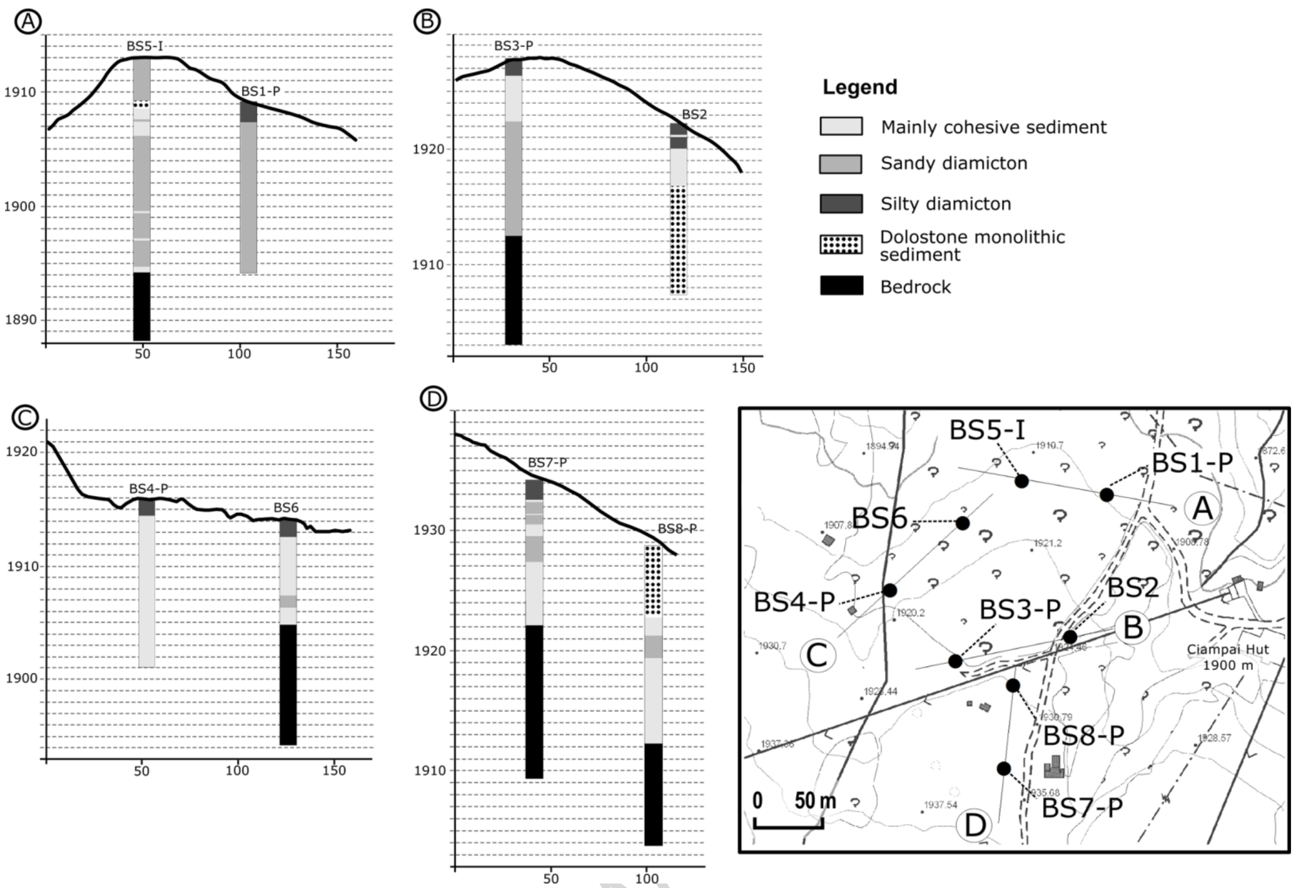

Fig. 3. Schematic cross-sections and simplified sediment types of the boreholes on the Pralongià plateau and their location within the Alta Badia valley. See Fig. 1 for location of sampling site.

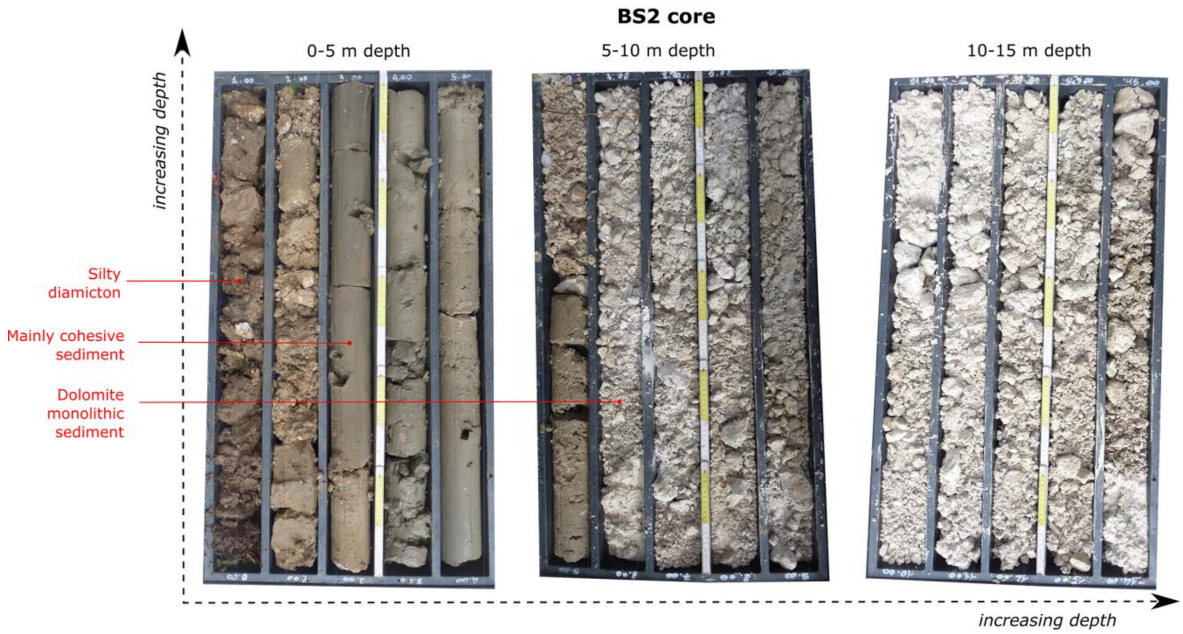

Fig. 4. Example of one of the eight cores from the Pralongià plateau: BS2 core (15-m deep).

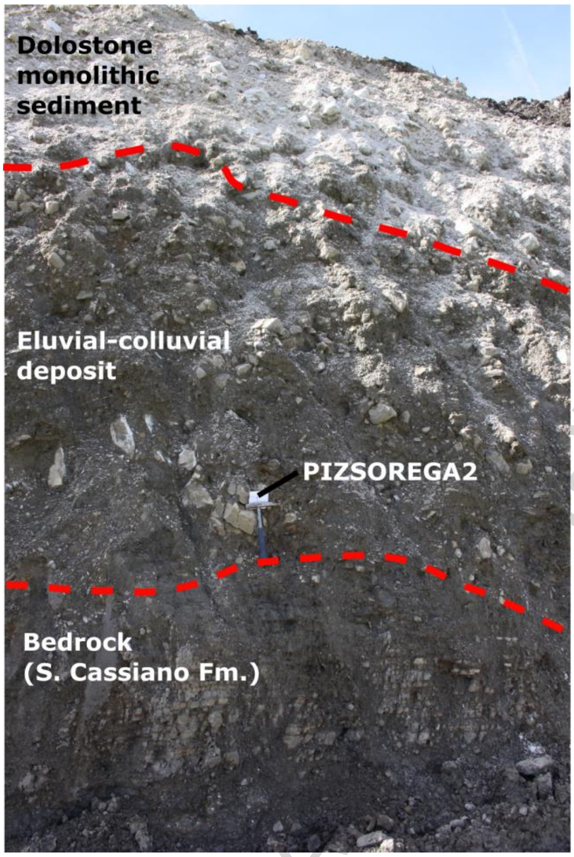

Fig. 5. Excavation wall, close to BS8-P borehole site, where PIZSOREGA2 sample was collected for radiocarbon dating. Dashed lines indicate the lithological boundary between different sediment types.

Table 1 Sediment types and morphogenetic interpretation of the stratigraphic records from the Pralongià plateau.

Sediment types	**Description**	**Morphogenetic interpretation**
Diamicton	Silty matrix with faceted and striated polygenic elements	Lodgement till
	Sandy matrix with clastic angular/sub-angular polygenic elements, sterile	Gravity-induced (debris flow-like) deposit
Cohesive sediment	Silt and clay with abundant polygenic elements	Eluvial-colluvial deposit
	Silt and clay with elements of the bedrock	Eluvial deposit
	Mainly silt and clay, organic-bearing	Stagnant water deposit
Dolostone monolithic sediment	Dolomite sandy matrix with clastic dolomitic elements, sterile	Gravity-induced (debris flow-like) deposit

5. Sedimentary and radiocarbon dating evidence

Each of the eight cores showed an individual litho-stratigraphy, with variations from core to core. However, it was possible to identify different types of sediments above the Triassic bedrock – the latter constituted by marls, marly limestones and calcarenites of S. Cassiano and Wengen formations – as shown in Table 1. The bedrock was reached in several drillings (BS3-P, BS5(I), BS6, BS7-P, BS8-P) at depths of 9.3 to 19 m.

The lowermost part of the cores prevalently contains cohesive sediments with some clasts from the alteration of the underlying bedrock.

The central part of the cores is generally constituted by sandy diamicton, a light brown sandy matrix with silt, which envelops angular to sub-angular polygenic elements, among which dolomite clasts are found. A monolithic sediment, similar in texture to sandy diamicton, was also encountered (cf. Fig. 4); it is made up of dolostone of varied particle-sizes. The monolithic nature of this sediment, the rather good sorting degree and the massive structure together with stratigraphic and geomorphological evidence which will be discussed further on (cf. this section and section 6), make unlikely a subglacial/englacial transport of the clasts. The sandy diamicton and monolithic sediment are devoid of organic matter. This probably indicates that they were deposited in unfavourable conditions for organic matter production (e.g. periglacial).

In most of the cores, silty diamicton was encountered from the top of the cores as far as 1.5/2 m in depth. The silty diamicton is composed of a dark silty matrix, which envelops polygenic elements of dolostone, marls and sandstones of variable shape and size. These elements appear as faceted and striated. These features enable to infer a glacial origin of the deposit.

The analysis of the stratigraphic records provided by the cores, with the fundamental help of radiocarbon dating results, finally led to the overall genetic interpretation of the deposits.

The sample taken from the excavation wall (Fig. 5) at the interface between bedrock and sediment gave the oldest age of the deposit, corresponding to 44,915±785 cal years BP.

5.1 Eluvial and/or colluvial deposits

In most of the cores (Fig. 3) cohesive sediments, including some clasts of the underlying bedrock, were interpreted as eluvial in origin, from bedrock weathering in subaerial conditions. It is likely that organic matter found within the eluvial deposits was leached from topsoil. Radiocarbon dating on a sediment sample from BS7 core (9.90-10 m deep), within the eluvial deposits, provided a calibrated (cal) age of 41,918±443 years BP (Fig. 6).

The sample taken within the eluvial deposit from BS8-P core (Fig. 6), between 14.50 and 14.60, was dated at 39,058±528 cal years BP. Radiocarbon dating on the sample taken within the eluvial deposit from BS8 core and between 16.40-16.50 m in depth, provided an age of 41,665±490 cal years BP. Sandy diamicton and dolostone monolithic sediments are interrupted or overlain by massive cohesive sediments, mainly made up of dark-coloured and organic-bearing silt with some polygenic elements, among which sub-angular granules and pebbles of dolostone are found. These deposits were interpreted as colluvial-eluvial deposits.

Radiocarbon dating of the sample from BS6 core (Figs. 3 and 6) (2.8 m deep), taken within the colluvial-eluvial deposit, was dated at 38,715±380 cal years BP (Tab. 2). However, considering its stratigraphic position, it is likely that the deposit is more recent than the age obtained owing to possible inclusion of organic-matter, older than the time of the emplacement of the deposit within the colluvial-eluvial sediments.

5.2 Stagnant water deposits

Within all the eight cores recovered at various depths (e.g. Fig. 6), cohesive and organic bearing sediments, ranging in thickness from some decimetres to 3 m, constituted by dark-coloured silt, were found including rare polygenic pebbles. A low-energy depositional environment was inferred for these silt deposits, although the topography of the area did not permit the storage of a large amount of water. Possibly, the area might have hosted stagnant water pools allowing fine suspended sediments to settle.

The sample taken from BS8-P core (Fig. 6), between 9.5 and 9.8 m in depth within the stagnant water deposit, was dated at 41,043±563 cal years BP. Since this age is older than that of the sample taken from the underlying eluvial deposit (between 14.50 and 14.60 m depth), it probably pre-dates the true age of the stagnant water deposit. It is likely that organic-matter older than the deposit was included in it.

5.3 Gravity-induced deposits

The central part of the cores (BS1-P, BS3-P, BS5(I), BS6, BS7-P, BS8-P) is generally made up of massive sandy diamicton (Fig. 3), which is dominated by a light brownish sandy matrix with a massive structure, which envelopes polygenic granules, pebbles and cobbles from angular to sub-angular in shape. These polygenic elements are prevalently made up of dolostone although marls and sandstones are not rare. No evidence of glacial erosion (striated and faceted granules) was found. Sandy diamicton reaches its highest thickness, more than 10 m, within BS1-P and BS3-P cores, and constitutes almost the entire BS5-I core. On the other hand, in BS6 core the sandy diamicton is limited to a thinner layer of only 1 m, overlain by a thick massive layer of cohesive sediment. Monolithic sediment, similar in texture to sandy diamicton, was also recovered; this is made up of whitish dolostone of varied particle-sizes, from fine sand to pebbles and some cobbles. No evidence of organic matter was found within the sandy diamicton and the dolostone monolithic sediment, letting us suppose that these deposits might have settled under glacial/paraglacial conditions. The sandy diamicton and the monolithic dolostone sediment seem to have been transported and accumulated by debris flows originating from the dolomite cliffs or by reworking/washout of possible rock avalanche deposits. The conditions and patterns for material transport to the plateau are described in section 6.

5.4 LGM lodgement till

In most of the cores examined (BS1-P, BS2, BS3-P, BS4-P, BS6-P) consolidated silty diamicton was encountered from the top of the cores up to 1.5/2 m in depth (Figs. 3, 4, 6). Silty diamicton is characterised by a dark silty matrix, which envelops abundant polygenic elements of dolostone, marls and arenites with variable shapes and sizes. These elements appear as faceted and striated and enable to infer a glacial origin for the deposit. Silty diamicton constitutes a sediment blanket partially covering the Pralongià plateau. For its textural features and its uppermost stratigraphic position, silty diamicton was interpreted as LGM lodgement till.

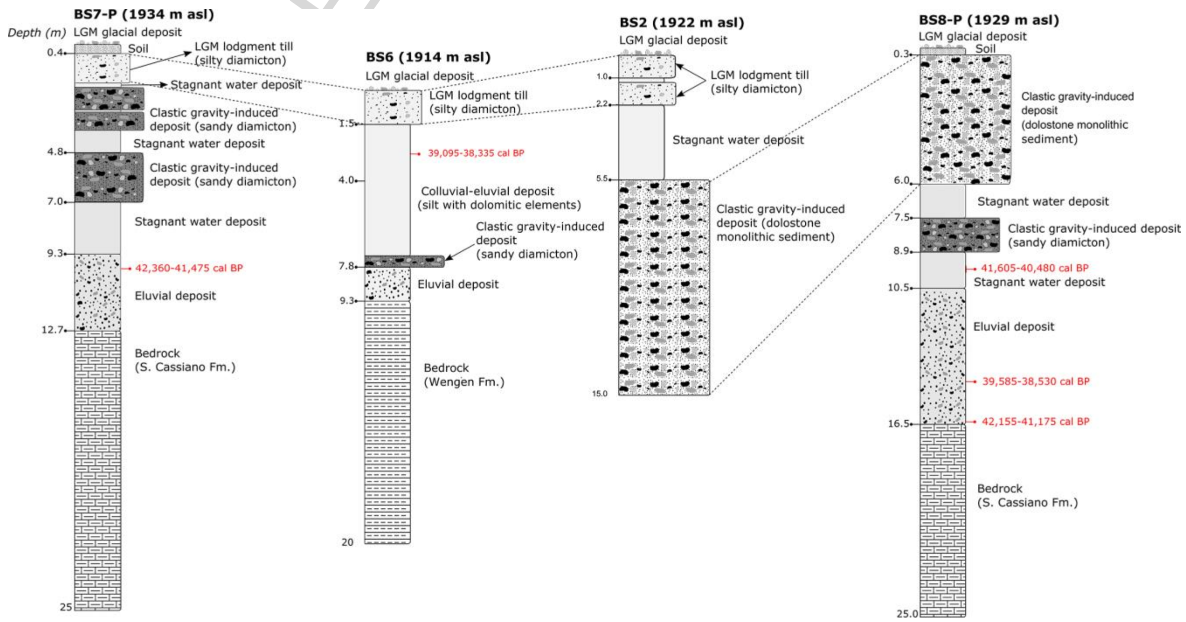

Fig. 6. Overview of sediment types constituting BS7-P, BS6, BS2 and BS8-P cores, stratigraphic units and radiocarbon ages.

Table 2 Results of radiocarbon dating on bulk organic sediment from samples collected on the Pralongià plateau.

Sample name	Sample lab code	Depth (m)	Altitude (m a.s.l.)	Material	$^{13}C/^{12}C$ ratio	Measured radiocarbon age (years BP)	Cal ka BP (2 sigma)	Interpreted genesis of the deposit
BS6	Beta - 395393	2.8	1911	Bulk organic soil	-24.5	34,180 ± 230	**39,095 – 38,335**	Colluvial-eluvial deposit
BS7-P	Beta - 395394	9.90-10	1924	Bulk organic soil	-24.0	37,510 +/- 340	**42,360 – 41,475**	Eluvial deposit
BS8-Pa	Beta - 395395	9.5-9.8	1919	Bulk organic soil	-23.3	36,420 +/- 290	**41,605 – 40,480**	Stagnant water deposit
BS8-Pb	Beta - 395396	14.5-14.6	1914	Bulk organic soil	-23.6	34,500 +/- 250	**39,585 – 38,530**	Eluvial deposit
BS8-Pc	Beta - 395397	16.40	1913	Bulk organic soil	-24.0	37,160 +/- 350	**42,155 – 41,175**	Eluvial deposit
PIZSOREGA2	Beta - 371854	2.5	1921	Bulk organic sediment	-23.5	41,280 +/- 620 BP	**45,700 – 44,130**	Eluvial deposit

6. Discussion

Considering the chronology and genesis of the deposits identified, possible evolution scenarios of the Pralongià landscape between 46,000 year BP and the LGM period was proposed (Fig. 7). These scenarios were compared to local and global palaeo-environmental records (e.g. palyno-stratigraphic records, $\delta^{18}O$ curves).

6.1 Pre-LGM period and emplacement of supraglacial gravity-induced deposits on the Pralongià plateau

In some cases, it is possible that radiocarbon ages pre-date the deposits; this might be due to colluvial processes that could be responsible for the inclusion of older organic remains within these deposits. However, the radiocarbon ages obtained are still significant because they indicate that between some 45 and 38 ka BP the Pralongià plateau was likely to have been ice-free and conditions enabling organic matter production occurred.

As previously mentioned, sandy diamicton, monolithic sediment and colluvial-eluvial deposits are dolostone bearing, even if there are no dolomite outcrops within the Pralongià plateau. This let us suppose that sediments might have been transported from sources outside the Pralongià plateau. Endoglacial or subglacial transport is excluded owing to the lack of evidence within the deposits and the dominance of dolostone monolithic angular material. Thus, significant gravity-induced input should be taken into account. It is likely that slope-instability processes – vast enough to reach the Pralongià plateau from the surrounding dolomite cliffs – took place. This hypothesis is supported by the fact that large-scale landslides are common during and after the LGM in the Italian Alps (e.g. Genevois et al., 2006; Soldati et al., 2006; Borgatti and Soldati, 2010; Carton, 2017; Rossato et al., 2018). The Masiere di Vedana rock avalanches (Mt. Peron, Belluno Province) are worthy of note in the Eastern Alps, with a total rock mass of 100 million m^3 and an extension of 5.5 km. These mass movements occurred within the Cordevole valley when the valley floor was still occupied by the Cordevole glacier, some 16-15 ka BP (Pellegrini et al., 2006).

However, it should be pinpointed that the isolation of the Pralongià plateau from the surrounding dolomite peaks – due to the presence of deep valleys bounding it – would have precluded landslide deposits from reaching the plateau. Nevertheless, this could have occurred in the presence of ice masses filling the valleys and hence, linking the dolomite cliffs to the plateau. In such a situation, supraglacial transport would have occurred (Fig. 7). At present, there are many examples of rock avalanches or debris flows occurring on glaciers in Alpine environments that travel for kilometres from their source areas (McSaveney, 1978; Kirkbride and Sugden, 1992; Fort, 2000, 2003; Jibson et al., 2006; Hewitt, 2009; Stoffel and Huggel, 2012). In glacial conditions, these types of mass movements can have an enhanced mobility and a remarkable runout, mainly due to the incorporation of ice and snow, which reduce the friction within the debris mass (e.g. Deline, 2009).

Considering the sedimentological features of the gravity-induced deposits analysed – particularly their scant sorting and the angular/sub-angular shape of the clasts and their monolithic nature – their origin can be related to the occurrence of a series of debris flows from dolomite cliffs or the wash out/reworking of rock avalanche deposits, which accumulated over the ice mass. According to our reconstructions (Fig. 7), between 38 ka BP and the LGM, large-scale slope movements detaching from the main ridges surrounding the

Pralongià plateau might have occurred. This would have required a large source area of dolostone, which can be identified in the Conturines (to the north) and/or in the Sassongher massifs (to the west) (Fig. 8).

If we suppose an ice bridge attaining 1900 m a.s.l. (Scenario 1 in Fig. 7), the only possible source area can be identified in the southern side of the Conturines massif, located some 5 km from the sampling site and characterised by a travel slope of 70%, from the cliff to the ice surface. This would be related to the surfacing of a physical barrier represented by a mountain ridge higher than 1990 m between the Sassongher and the Pralongià, which would have prevented sediment to reach the plateau (Fig. 9a). If the ice surface is raised to 2010 m (Scenario 2 in Fig. 7; Fig. 9b), two source areas can be identified: i) one along the slopes of the Sassongher massif (W), 4 km away from the sampling site, ii) the other in correspondence with the southern Conturines cliff; both with a subvertical travel slope, calculated from the top of the cliff to the ice surface.

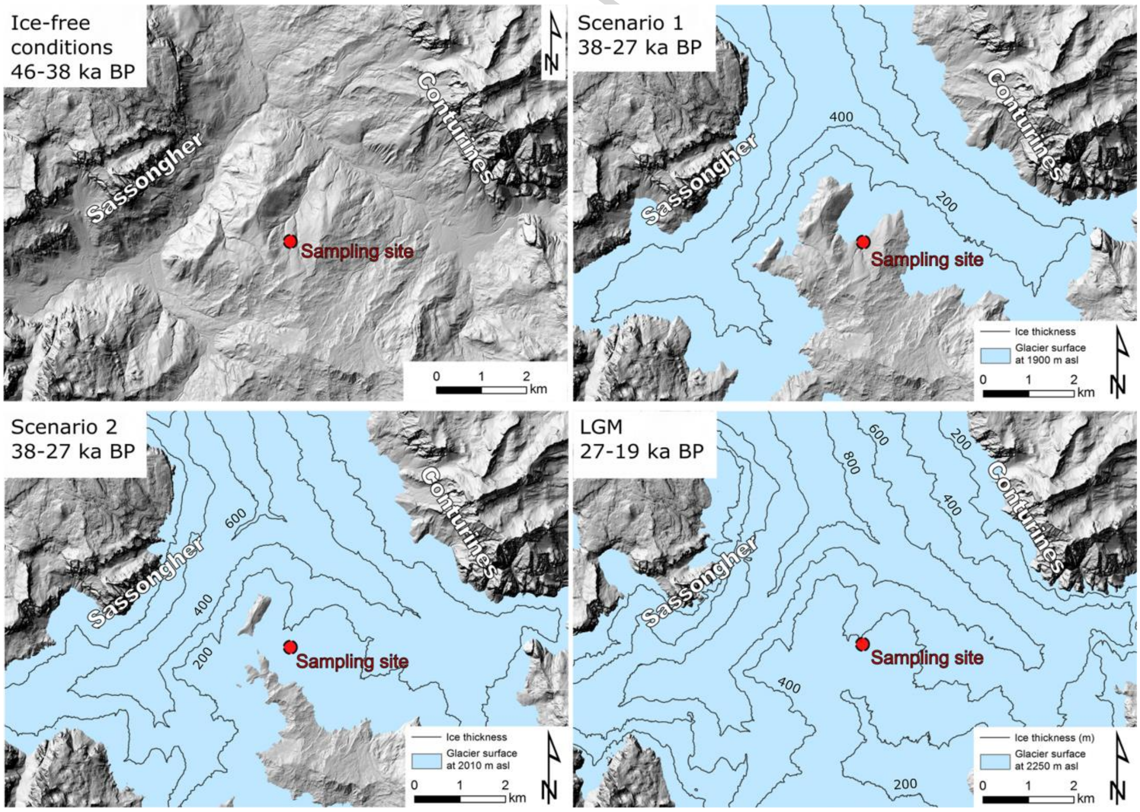

Fig. 7. Ice cover reconstructions. Between 38 and 27 ka BP an ice bridge is supposed to have connected the main dolomite massifs (Sassongher and Conturines) within the Alta Badia valley to the Pralongià plateau, before the onset of full glacial conditions (LiDAR data courtesy of Servizio cartografia provinciale

coordinamento geodati, Autonomous Province of Bolzano). For scenarios 1 and 2 see Fig. 9a and 9b respectively.

Fig. 8. Southwestern view of the Alta Badia valley. Extensive debris cones due to gravity-induced slope processes characterise the foot of the Sassongher massif (on the left) and of the Conturines southern cliff (in the background). The Pralongià plateau stands in the central part of the picture, to the right of the Sassonger massif and opposite the Conturines southern cliff (photo by F. Planinschek, courtesy of Tourist Board Alta Badia).

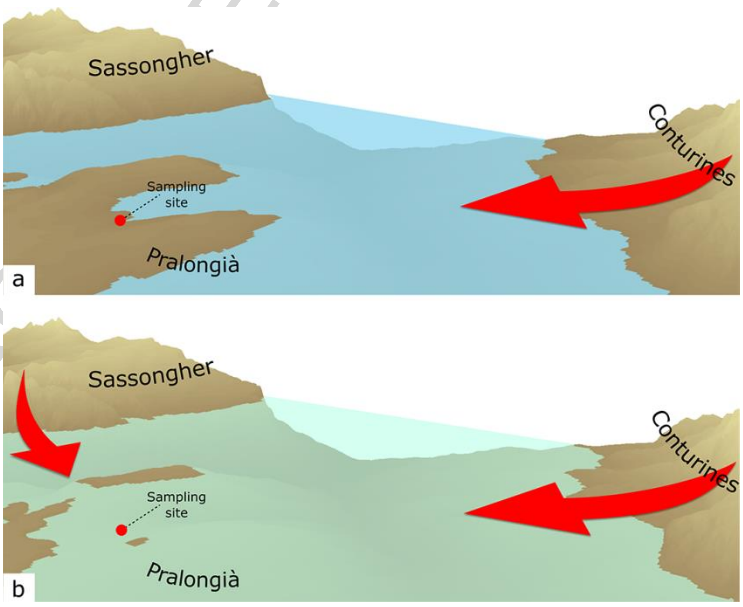

Fig. 9. Possible sediment sources within the dolomite ridges surrounding the Pralongià plateau. 3D reconstruction of the ice surface a) at 1900 m a.s.l.; b) at 2010 m a.s.l.

6.2 Correlation with local and global palaeo-environmental and palaeo-climatic data

Radiocarbon dating showed that the bulk organic sediments found at the Pralongià plateau could be attributed to the MIS 3 period. The radiocarbon ages indicated that the Pralongià plateau was likely to have been ice-free between at least 45 and 38 ka BP.

No other MIS 3 records are currently known from the Italian Dolomites except for radiocarbon dating on cave bear remains found at about 2800 m a.s.l., within a cave on the southern side of the Conturines massif. Originally, bear remains were dated at 44 ka BP (cf. Döppes et al., 2011 and references therein) but ages were recently revised by Spötl et al. (2018) and attributed to a period older than MIS 3, possibly the Last Interglacial. Thus, it is necessary to take a look at the larger palaeo-environmental database obtained from other Alpine regions and surroundings.

We generally know from literature that during MIS 3 the European ice caps receded from their outer positions achieved in MIS 4, and extensive portions of the landscape were abandoned by the ice; sea level stood between -55 and -90 m below the present level. MIS 3 was characterised by intense and abrupt climate changes, indicated by significant $\delta^{18}O$ variations (Rabassa and Ponce, 2016 and references therein). The climate pattern revealed by the $\delta^{18}O$ curve from Greenland ice cores resemble the one from northern Alpine speleothems (Moseley et al., 2014). In this context, the $\delta^{18}O$ curve from Greenland ice cores (e.g. Svensson et al., 2008) can be considered a reliable climate proxy for central Europe. The time frame in which our samples stand (46-38 ka BP) is characterised by five rapid warming events in Greenland, known as Greenland Interstadials (GI) 12-8, separated by four stadials (GS) 12-9 (Fig. 10). The ^{14}C ages of BS6, BS7-Pa and BS8-Pa, b, c fall partly or totally within stadial periods (Fig. 10), witnessing that even during the latter event the area was in ice-free conditions. On the other hand, PIZSOREGA2 sample can be attributed to GI-12, during which period a significant interstadial phase was recorded in speleothems (between 50-45 ka BP) in the northern Alpine foreland, when air temperature was some 4 °C lower than today (Tütken et al., 2007). However, the level of precision of the radiocarbon ages available does not permit their unequivocal relation to a single peak/down in the $\delta^{18}O$ curve.

The interpretation of continuous pollen profiles covering MIS 3 offers a possibility to learn more about vegetation and climate conditions in the Alps and surrounding areas. Boreal and continental conditions mainly prevailed during all MIS 3 at the northern Alpine foreland, which during stadials was dominated by arctic tundra, with open landscapes and was characterised by loess accumulation (de Beaulieu and Reille, 1992; Reille et al., 1998; Spötl et al., 2018 and references therein). This is in contrast with palyno-stratigraphic data from the southern Alpine foreland, according to which afforestation persisted for all MIS 3 and an estimated surface air temperature around 7 °C, with 600 mm/year of rainfall, characterised the stadial intervals (Pini et al., 2010).

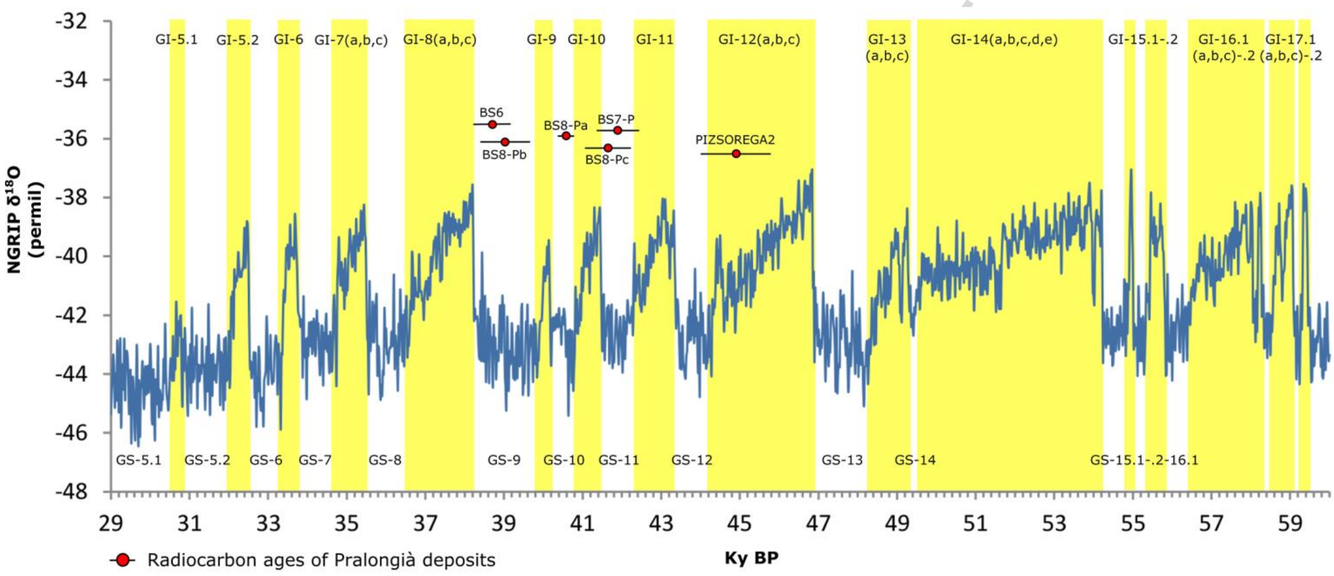

Fig. 10. Greenland $\delta^{18}O$ ice core chronology relevant to the MIS 3 (data from Svensson et al., 2008). Glacial Stadials (GS) and Glacial Interstadial (GI) were numbered according to Rasmussen et al. (2014).

Palaeo-environmental data from mountain regions of Central Europe demonstrated that during most of MIS 3 the main valleys were ice-free (Ivy-Ochs et al., 2008 and references therein; Engel et al., 2010). Climate deterioration in the Northern and Southern Alps is witnessed by the disappearance of the cave bear between some 35-31 ka BP (Spötl et al., 2014), as well as by remains of cold climate fauna dating back to 30 ka BP in the Carnic Prealps (South-Eastern Alps) (Carrera et al., 2018). Full glacial conditions occurred only since the transition between MIS 3 and MIS 2.

Between 46 and 38 ka BP, the global atmospheric surface air temperature – ranging between -11 to -13.6 °C with respect to the present (Bintanja et al., 2005) – was comparable to the period following the LGM, around 18-16 ka BP (Fig. 11). Additionally, the estimated Eurasian ice volume, between 46 and 38 kyr BP (from -34.8 to -32 sea level equivalent relative to the present; Bintanja et al., 2005), was similar to the one occurring between 16 and 15 ka BP. Between 17 to 15 ka BP, a stadial period was recognised in the Alps, the Gschnitz stadial (cf. Ivy-Ochs et al., 2008 and references therein). Thus, it is likely that between 46 and 38 ka BP, the glacier surface was more extensive than today and probably comparable to the Lateglacial, approximatively between 17 and 15 ka BP. During this period, 80%-90% of LGM glacier volume was already lost and glacier termini were situated well inside the Alpine valleys (Ivy-Ochs et al., 2008). Literature data and radiocarbon ages here presented seem to confirm that the Pralongià plateau was in ice-free conditions for most of MIS 3.

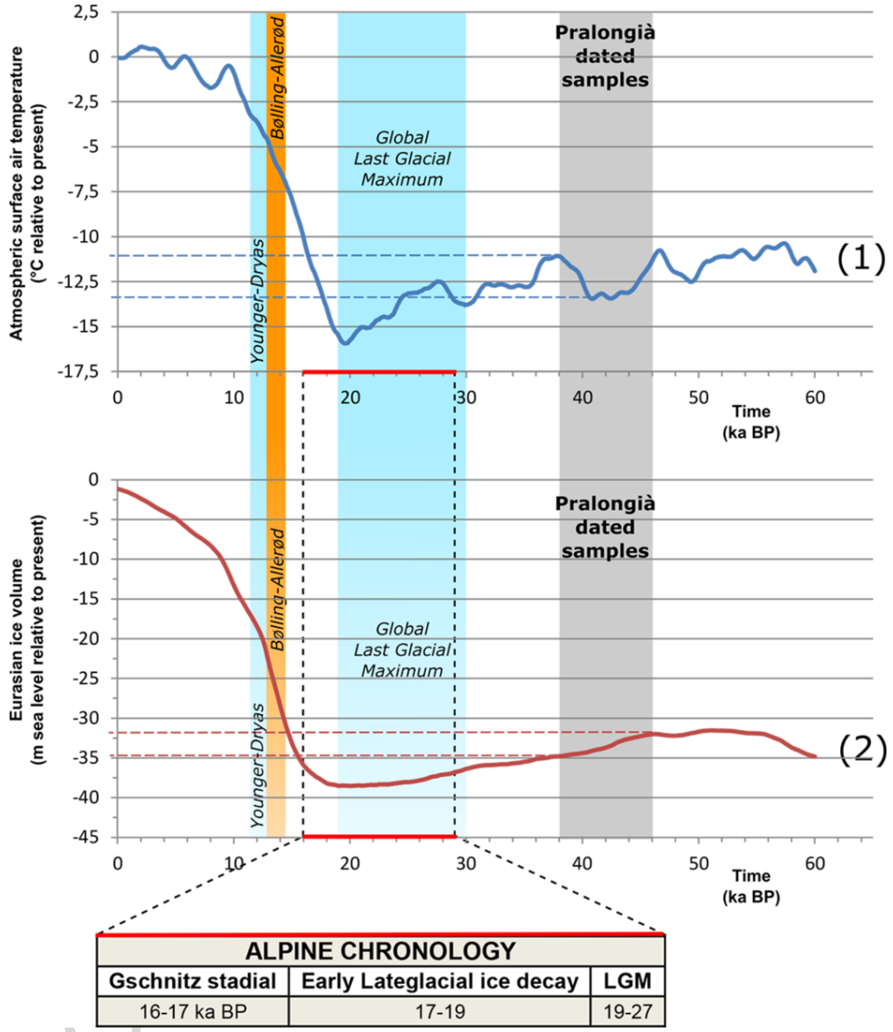

Fig. 11. Correlation with global and regional palaeo-climate data: (1) global variation of atmospheric surface air temperature with respect to to the present (°C) and (2) varation of Eurasian ice volume with respect to the present in sea level equivalent (m) (data from Bintanja et al., 2005); timing of Younger-Dryas and Bølling Allerød climate events according to Rasmussen et al. (2014); timing of Global Last Glacial Maximum event according to Lambeck et al. (2002); Alpine chronology according to Ivy-Ochs, 2015 and references therein.

7. Conclusions

The study was based on the analysis of stratigraphic data from an excavation wall and from eight continuous-coring boreholes ranging in depth from 15 to 25 m, carried out on the formerly glaciated Pralongià plateau in the Eastern Italian Dolomites. Radiocarbon dating results and the interpretation of stratigraphic data, supported by geomorphological field surveys and remote sensing data analyses, enabled us to conclude that:

I. Between 45 and 38 ka BP the Pralongià plateau (ca. 2000 m) was ice-free.

II. Between 38 ka BP and the onset of full-glacial conditions (LGM ~27 ka BP) clastic gravity-induced sediments were deposited within the study site.

   a. Debris flows or also possibly the wash out/reworking of rock avalanche deposits were considered the main processes providing sediment supply. It should be noted that large-scale landslides, including rock avalanches, might have occurred in the area also due to earthquakes that could be related to neotectonic activity for which geomorphological evidence was recognised in the Alta Badia valley (Corsini and Panizza, 2003).

   b. The main source area could be identified in the Conturines massif (NE of the Pralongià plateau) or, alternatively, in correspondence with the Sassonger massif (W of the plateau).

   c. Supraglacial transport is supposed to have played a role in the emplacement of the gravity-induced deposits over the plateau.

III. Full glacial conditions occurred afterwards, in accordance with literature data (cf. Monegato et al., 2017), probably since about 27 ka BP. During this period, the Pralongià plateau was covered by an extensive and rather thick ice cap.

The study carried out on the Pralongià plateau resulted in the first Pre-LGM record of sedimentation and palaeo-environmental conditions inside the Eastern Dolomites in the period between 46 and 38 ka BP. Moreover, this study intends to provide the ground basis for further insights on the environmental conditions relevant to the Pre-LGM period at high elevations in the Alps.

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