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Subglacial carbonate deposits as a potential proxy for glacier's existence

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Abstract. The retreat of ice shelves and glaciers over the last century provides unequivocal evidence of recent global warming. Glacierets (miniature glaciers) are an important component that highlights the global retreat of glaciers, but knowledge of their behaviour prior to the Little Ice Age is lacking. Here, we present subglacial carbonate deposits from a recently exposed surface previously occupied by the disappearing Triglav Glacier (southeastern European Alps) that may elucidate the glacier's existence throughout the entire Holocene since their maximum uranium-thorium (U-Th) ages suggest their possible preservation since the Last Glacial Maximum and Younger Dryas. These thin deposits, formed by regelation, are easily eroded if exposed during previous Holocene climatic optima. The age data indicate the glacier's present unprecedented level of retreat since the Last Glacial Maximum, and the potential of subglacial carbonates as additional proxies to highlight the extraordinary nature of the current global climatic changes.

1 Introduction

Glaciers respond to climatic changes making them valuable archives with which to study the effects of past and current climatic changes (Benn and Evans, 2010). Their retreat globally over the last century provides evidence in support of current global climate change even though the decrease of summer insolation in the Northern Hemisphere favours climate cooling (Solomina et al., 2015; IPCC, 2018). The uniqueness of this trend can only be understood when compared to past retreats and advances of different types of glaciers throughout the entire Holocene.

Despite their small size, 'glacierets', defined as miniature glaciers or ice masses with little or no movement for at least two consecutive years (Kumar, 2011), occupy a significant volume fraction at regional scales, and are thus an important target for palaeoclimate studies (Bahr and Radić, 2012). Accordingly, many glacierets are closely monitored and studied (Gądek and

Kotyrba, 2003; Grunewald and Scheithauer, 2010; Gabrovec et al., 2014; Colucci and Žebre, 2016), but the peculiarity of current global climate change requires more evidence from different proxies and from further in the past.

The data that informs a glacier's dynamics in the past can be provided by subglacial carbonate deposits (Hallet, 1976; Sharp et al., 1990). These are thin carbonate crusts formed in a microscopic space between the ice and bedrock due to regelation at the glacier base on the lee side of a bedrock protuberance (Hallet, 1976; Lemmens et al., 1982; Souchez and Lemmens, 1985), and can provide information on chemical and physical processes present at the time of their formation (Hallet, 1976).

Unlike other remnants of glacial deposits (e.g., moraines), subglacial carbonates may be eroded in a few decades (Ford et al., 1970), which is also evident in literature where generally 'recently exposed' subglacial carbonates are studied. They have been reported from deglaciated areas of northern America (Ford et al., 1970; Hallet, 1976; Refsnider et al., 2012), northern Europe and European Alps (Lemmens et al., 1982; Souchez and Lemmens, 1985; Sharp et al., 1990; Lacelle, 2007; Thomazo et al., 2017), Tibet in Asia (Risheng et al., 2003), and Antarctica (Aharon, 1988; Frisia et al., 2017). U-Th isotope analyses remains the main dating technique for these carbonates, whilst the ^{14}C technique is invalidated by modern carbon contamination (Aharon, 1988).

The deposits recently exposed by the drastic retreat of the Triglav Glacier (Fig. 1) over the last 100 years, from ca. 46 ha (extending between 2280 and 2600 m.a.s.l.) to ca. 0.5 ha (between 2439 and 2501 m.a.s.l.) (Gabrovec et al., 2014), offer a unique opportunity to gain additional knowledge of glacier's behaviour in the past. The Triglav Glacier extends from the northeastern side of Mount Triglav in the Julian Alps (Fig. 2 & 3), Slovenia's highest mountain and consisting of Upper Triassic limestone and dolostone (Ramovš, 2000; Pleničar et al., 2009). This region's montane climate is characterised by precipitation from moisture-bearing air masses from Mediterranean cyclones, which are most frequent in autumn and late spring, and by frequent temperature change from below freezing to above freezing (Komac et al., 2020).

At present, the glacier is one of only two remaining ice masses in Slovenia since the last extensive Pleistocene glaciation (Bavec and Verbič, 2011; Ferk et al., 2017). The known extent and behaviour of the Triglav Glacier spans from the present to the Little Ice Age (LIA), the cool-climate anomaly between the Late Middle Ages and the mid-19th century (Grove, 2004; Nussbaumer et al., 2011), and is based on geomorphological remnants, historical records and systematic monitoring since 1946 (Gabrovec et al., 2014). Together, this information reveals its on-going retreat from the plateau-type to the present glacieret-type (Colucci, 2016; Colucci and Žebre, 2016) (see also Supp. Fig. S1 & S2), with a rate of retreat at around 580 kg/m^2/yr (1992-2008) (Gabrovec et al., 2014). The extensive retreat of the glacier has exposed a glaciokarst environment (Fig. 2 and Supp. Fig. S2) comprising a range of erosional (shafts, karrens, polished surfaces and roches moutonnées) and depositional (moraines, boulders, till, carbonate deposits) features (Colucci, 2016; Tičar et al., 2018; Tóth and Veress, 2019).

Here, we present preliminary geochemical and petrological data of the recently exposed subglacial carbonate deposits due to glacier retreat. The aim is to highlight the occurrence of deposits in terms of their possible preservation since the Last Glacial Maximum, discuss the complexity of the deposit and validate the results. This relates to the present climate regime of rising temperatures and global retreat of glaciers.

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6 Methods

The extent of the Triglav Glacier has been measured annually since 1946 and systematically photographed since 1976 (Meze, 1955; Verbič and Gabrovec, 2002; Triglav Čekada and Gabrovec, 2008; Triglav-Čekada et al., 2011; Triglav-Čekada and Gabrovec, 2013; Gabrovec et al., 2014; Del Gobbo et al., 2016), using a panoramic non-metric Horizont camera. The photos were transformed from a panoramic to central projection in order to allow the calculation of the area and estimation of the volume (Triglav-Čekada et al., 2011; Triglav-Čekada and Gabrovec, 2013). The early measurement technique included measuring tape and compass, which enabled to measure the glacier's retreat from coloured marks on the rocks around the glacier (Meze, 1955). Accurate geodetic measurements began in the 1990s: standard geodesic tachymetric measurements, UAV photogrammetric measurements (from both the ground and air), GPS measurements, and LIDAR (Triglav Čekada and Gabrovec, 2008; Gabrovec et al., 2014). In addition, several extensive field campaigns were conducted throughout the year 2018 with the focus on the central part of Triglav Plateau at the side of the present and former glacier (Fig. 1), and five carbonate deposit samples (Fig. 4) were collected at multiple localities (Fig. 1) for further laboratory analyses.

A hand drill was used in order to obtain powdered samples for geochemical analysis, performed in areas of the deposit consisting of dense and thick enough crystals. Prior to and after each drilling, the surface was cleaned with deionized water and dried under clean air. Drilling was performed with a 0.6 mm drill bit in a clean environment, targeting carbonate cement. A stainless steel spatula and a weighing paper were used to harvest the drilled powder and transfer it into a clean 0.5 ml sterile vials.

Five thin sections (30 – 50 μm) were examined using an Olympus BX51 polarising microscope equipped with an Olympus SC-50 digital camera. Due to the fragility of the samples, they were embedded in Epoxy resin under vacuum before being cut and polished.

The mineralogy of twelve (sub)samples was determined by X-ray diffraction (XRD) using a Bruker D2PHASER diffractometer equipped with an energy dispersive LYNXEYE XE-T detector, located at the Karst Research Institute ZRC SAZU, Slovenia. Powdered samples were scanned from 5 to 70° 2θ at a 0.02° 2θ/0.57 s scan speed. The diffractograms were interpreted using EVA software by Bruker (DIFFRACPlus 2006 version).

Five (sub)samples were dated by the uranium-thorium (U-Th) method at the University of Queensland, Australia. To assure that samples had sufficiently high U/Th ratios for dating, they were first measured by ICP-MS for their trace element concentrations. U-Th age dating was carried out using a Nu Plasma multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) in the Radiogenic Isotope Facility (RIF) at the School of Earth and Environmental Sciences, The University of Queensland (UQ). Ages were corrected for non-radiogenic ^{230}Th incorporated at the time of deposition. Age errors are reported as 2σ uncertainties. Full details of the method are provided in the supplementary material – Table S2.

The stable isotope laboratory at the University of Melbourne, Australia, was used to analyse five (sub)samples for both $\delta^{13}C$ and $\delta^{18}O$ isotopes. Analyses were performed on CO_2 produced by the reaction of the sample with 100% H_3PO_4 at 70°C using continuous-flow isotope ratio mass spectrometry (CF-IRMS), following the method previously described in Drysdale et al.

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(Drysdale et al., 2009) and employing an AP2003 instrument. Results are reported using the standard δ notation (per mille ‰) relative to the Vienna PeeDee Belemnite (V-PDB scale). The uncertainty based on a working standard of Cararra Marble (NEW1) is 0.05‰ for $\delta^{13}C$ and 0.07‰ for $\delta^{18}O$.

3 Results

Subglacial carbonate deposits occur on the lee sides of small protuberances on a bare polished and striated limestone bedrock surface in the immediate vicinity of the Triglav Glacieret. They are most abundant on the bedrock recently uncovered by the retreating ice, and their occurrence rapidly decreases with the distance from the edge of the present glacieret termination. They are fluted and furrowed crust-like deposits characterized by brownish, greyish or yellowish colour. The deposits do not exceed 0.5 cm in thickness and in some cases are internally laminated.

3.1 Mineralogical and petrographic data

X-ray diffraction (XRD) analysis shows that the carbonate deposits mostly consist of calcite; and mixtures of calcite with small amounts of aragonite XRD has also confirmed the calcite composition of the host rock (Supp. Fig. S8). Petrographic study has allowed the identification of different fabrics (Fig. 5). Due to the similarities of subglacial carbonate textures to those of speleothem deposits, we have used when possible the formal terminology of Frisia and Borsato (2010) (Frisia and Borsato, 2010):

Primary calcite fabrics are composed of transparent crystals with uniform extinction. The first crystals to form directly over the bedrock are short columnar (length to width ratios < 6:1) crystals from 50 to 200 µm long (Supp. Fig. S9 and S10). Columnar (L/W ratios ~ 6:1) and elongated columnar (L/W ratios > 6:1) crystals up to 2 mm long and 0.5 mm wide constitute the most abundant fabric. Depending on the angle of the lee side of bedrock protuberances, columnar calcite crystals grow either perpendicularly to the host rock (Fig. 5a) or with a lower angle, generally oriented downslope (Supp. Fig. S9). In some areas, the younger crystals crosscut the main direction of crystal growth of the previous layer, resulting in crystal boundaries resembling unconformities (Supp. Fig. S9).

Primary aragonite fabrics consist of acicular crystals (L/W ratio >>6:1) generally growing outwards from a common point in the shape of fans. In some areas of the crusts, these fans are aligned in bands interlayered with very dark, dense micrite and transparent equidimensional calcite crystals, forming layered textures (Fig. 5b, Supp. Fig. S9d).

Aragonite-to-calcite replacement fabrics are characterised by calcite crystals of variable size and patchy extinction patterns. They contain abundant fibrous inclusions interpreted as aragonite relicts that either are aligned in layers or unevenly distributed throughout, which results in very irregular textures (Supp. Fig. S9def). Micrite and microsparite is often associated with aragonite relicts.

3.2 Geochemical data and ages

Stable carbon and oxygen isotope ratios ($\delta^{13}C$ and $\delta^{18}O$) of the subglacial carbonate yielded average values of 1.35 ± 0.05 ‰ for $\delta^{13}C$ and –4.32 ± 0.07 ‰ for $\delta^{18}O$ (relative to the V-PDB; Supp. Table S1).

The U-Th ages yielded considerably older ages than expected: 23.62 ka ± 0.78 ka, 18.45 ka ± 0.70 ka and 12.72 ka ± 0.28 ka, respectively (Supp. Table S2). The results indicate that these subglacial carbonate dates fall within the Last Glacial Maximum and the Younger Dryas (YD). In addition, two U-Th ages of stratigraphically younger cement of the thickest obtained sample yielded 3.85 ka ± 0.09 ka and 1.96 ka ± 0.04 ka, indicating the presence of thick glacieret to cause regelation also during these periods, or recrystallisation.

4 Subglacial carbonate deposits

The fluted and furrowed morphology of carbonate deposition parallel to the apparent former ice-flow direction, some of the crystal textures, the location of the samples and the age data imply a subglacial origin of the carbonate crusts. The presence of ice-flow oriented calcite crystals suggests that precipitation was strongly influenced by the mechanical force of the ice movement. Similar fabrics occur in different types of tectonic veins, as for instance, slickensides, where crystals grow obliquely to the sheets in shear veins, indicating the general shear direction (Bons et al., 2012). Previous studies on subglacial carbonates have considered the orientation of calcite parallel to the ice flow as an evidence of its growth in a thin water film confined by sliding regelation ice (Hallet, 1976), and deformation structures such as folds and fractures, the result of glacially imposed stress (Sharp et al., 1990).

The variability of fabrics of the studied crusts and, specially, the presence of aragonite coexisting with calcite indicate spatial and/or temporal variability in local subglacial water chemistry. The most important parameters controlling the precipitation of aragonite versus calcite appears to be the $CaCO_3$ saturation state, the Mg/Ca ratio in the waters (De Choudens-Sánchez and González, 2009) and/or rapid CO_2 degassing rates (Fernández-Díaz et al., 1996; Jones, 2017), with aragonite precipitation favoured by high Mg/Ca ratios (Rossi and Lozano, 2016) in low supersaturated solutions. The studied deposits grow over carbonate bedrock with prevailing limestone and some dolostone (Jurovšek, 1987; Ramovš, 2000), so high Mg/Ca ratio in the water partially could be the trigger for the precipitation of aragonite.

The U-Th ages of LGM and YD are in good accordance with the glacier's history when it was expected to be thick enough to cause regelation which additionally strengthens the argument for carbonate's subglacial origin. However, aragonite-to-calcite replacement fabrics pose a challenge to determine whether all subglacial carbonate crystals were primarily aragonite and complete recrystallisation to calcite in places left no traces of replacement fabrics, which may provide a false identification of calcite fabrics as primary. This, in turn, may lead to inaccurate interpretation of the U-Th ages (Bajo et al., 2016). Previous studies in corals and speleothems have shown that the diagenetic transformation of aragonite into calcite can affect the accuracy of U-Th dating (Ortega et al., 2005; Scholz and Hoffmann, 2008; Lachniet et al., 2012; Bajo et al., 2016; Martín-García et al., 2019). This is mostly due to the uranium loss associated with the process (Lachniet et al., 2012; Bajo et al., 2016), which usually leads to older-than-true U-Th ages. However, the extent of uncertainty can be very variable depending on several factors such as the percentage of initial aragonite and the moment of the aragonite to calcite transformation (Bajo et al., 2016), the possible additional redistribution of Th (Ortega et al., 2005; Lachniet et al., 2012) or the degree of opening of the system during diagenesis (Ortega et al., 2005; Martín-García et al., 2019).

Based on the U concentration in samples within this study (in ppm; Supp. Table S2), it is notable that the youngest sample (2 ka; T.03_b1) has 1.77 ppm of U concentration, whilst two of the old samples (LGM and YD; T.01_a1 and T.03_a1) have around 0.41 and 0.46 ppm of U concentration, respectively. This could indicate U-loss during aragonite-to-calcite recrystallisation and consequently provide older-than-true ages, or contrary, that these two samples represent primary calcite with non-preferential incorporation of U in calcite with respect to aragonite and thus providing to be the most reliable. In case of the first possibility, the oldest sample (24 ka; T.05) has relatively high U concentration (1.33 ppm), which would indicate less loss of U but still provide data that subglacial carbonates may date back to the last glacial period. In case of the second possibility, the ages of T.03_a1 and T.03_a2 in correct stratigraphic order would strengthen the reliability of the results. Aharon (1988) used U-Th method for dating two samples with a combination of aragonite and calcite fabrics with high but also variable U content (23.2 and 41.4 ppm), however, the indistinguishable dates compared to the ones of pure aragonite led to conclusion that the dates are reasonably good estimate. Nevertheless, due to the external Th incorporated into the samples, he regarded the dates as "maximum ages", which, in this case, is the appropriate approach also with the dates discussed in this study. Similar U-Th ages (19-21 ka) were reported also from northern Canada (Refsnider et al., 2012), however, the carbonate fabrics were not identified and discussed. The U-Th dates from Antarctica by Frisia et al. (2017) and radiocarbon dates from French Alps by Thomazo et al. (2017) were performed on calcites. More studies should therefore be done in this direction to positively confirm the LGM and YD ages of carbonates, and especially to gain the high-resolution dates to construct the whole timeline of subglacial carbonate precipitation. Nevertheless, since three of our dates fall in the period of 12 – 24 ka, we will proceed with discussion of their susceptibility to weathering and its implication to glacier's existence.

The cold Alpine environment during the glacial period with low biological respiration rates is evident in the relatively high $\delta^{13}C$ signal, also reported by others (Lemmens et al., 1982; Fairchild and Spiro, 1990; Lyons et al., in press). In addition, the (re)freezing of the subglacial water causes supersaturation with respect to carbonate and the non-equilibrium conditions produced by this process can affect the stable isotopic composition of the subglacial carbonate, usually leading to isotopic enrichment in the carbonate minerals (Clark and Lauriol, 1992; Courty et al., 1994; Lacelle, 2007).

The $\delta^{18}O_{PDB}$ of subglacial carbonate can be transformed into $\delta^{18}O_{SMOW}$ using the equation $\delta_{SMOW} = 1.03037\ \delta_{PDB} + 30.37$ (Faure, 1977). The mean values of subglacial carbonate $\delta^{18}O_{SMOW}$ would therefore be 25.92‰, ranging from 27.44 to 24.75‰. Using the fractionation factor of 1.0347 for calcite and water at 0°C (Clayton and Jones, 1968) and the δ_{SMOW} values of subglacial carbonate, we obtain $\delta^{18}O_{SMOW}$ values ranging from –7.02‰ to –9.62‰. On the other hand, if assuming calcite crystals could have all originated primarily as aragonite crystals, we can use the fractionation factor of 1.0349 for aragonite and water at 0°C (Kim et al., 2007) and obtain relatively similar $\delta^{18}O_{SMOW}$ values ranging from –7.21‰ to –9.81‰. This relates to the average Triglav Glacier ice meltwater values ($\delta^{18}O_{SMOW}$ = –9.3‰) measured in the summer 2018 (Carey et al.,

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in press). However, it is slightly heavier when compared to the glacier ice samples that ranged between –10.0‰ and –12.7‰. The reason could be that water in equilibrium with the growing ice is progressively impoverished in heavy isotopes (Jouzel and Souchez, 1982), or simply that the remnants of present remaining ice has different isotopic ratio than the basal ice at the time of carbonate precipitation, for which is also known that represents a large range of isotopic composition (Lemmens et al., 1982). However, the geochemical study of the present Triglav area ice (Carey et al., in press) showed that ice samples found within the cave of Triglavsko Brezno Shaft (see Fig. 1 for location) are much lighter in deuterium compared to the Triglav Glacier, which suggests that they were deposited during colder, perhaps even Last Glacial Maximum, times, indicating possible remains of the old remnant of the Triglav Glacier, constraining the implications that the Triglav Glacier was constant during the Holocene.

5 Implications for continuously existing glacier during the Holocene

The LGM age is the first physical evidence to prove the LGM Triglav Glacier, whilst the YD age is related to the end of the Alpine Late Glacial, when glaciers advanced markedly (Ivy-Ochs et al., 2009) and persisted until the earliest Holocene (Solomina et al., 2015).

Glacierets of southern Europe, including the Triglav Glacier, have generally been viewed as relicts of the LIA, with discontinuous presence due to the Holocene Climatic Optimum (HCO) (Grunewald and Scheithauer, 2010), a period of high insolation and generally warmer climate between 11,000 and 5,000 years ago (Renssen et al., 2009; Solomina et al., 2015).

Being prone to fast weathering (Ford et al., 1970), subglacial carbonate deposits are generally found only on recently deglaciated areas (Ford et al., 1970; Sharpe and Shaw, 1989). The Triglav Glacier area is no exception, and the relatively recent exposure of the deposits is also evidenced by not being documented in the literature (Meze, 1955; Šifrer, 1963, 1976, 1987) until the year 2005 (Hrvatin et al., 2005; Gabrovec et al., 2014).

To provide the theoretical numerical data of chemical denudation of the subglacial carbonate, we can summarise selected chemical denudational rate of limestones (Table 1).

Chemical denudation rates on carbonate rocks can vary from ca. 0.009 to 0.14 mm/year (Gabrovšek, 2009). Taking the low and high extreme values for, e.g., 6 ka during the HCO, the denudation would be between 54 and 840 mm, so the exposed 5 mm thick subglacial carbonate would have been denuded in this time.

In addition, carbonate surfaces in periglacial areas are exposed not only to chemical weathering but also to intensive frost weathering, promoting disintegration of depositional features (Matsuoka and Murton, 2008). In case of a glacier retreat beyond the subglacial carbonates, the re-advance of the glacier would abrade the deposits with material eroded from surrounding mountain face. Therefore, had the subglacial carbonate been exposed in the past, it would be expected to be eroded by dissolution, frost weathering, or by abrasion.

Organic matter (charchoal/wood) from a non-vegetated, scree-covered moraine ca. 300 m below the main ice patch of the Triglav Glacier (as it stood in the year 2006) was analysed in the radiocarbon (^{14}C) laboratory in Erlangen, Germany. The ^{14}C

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result yielded 5604-5446 BP age, which provides additional evidence of pre-LIA, and post-LGM and post-YD ice cover (unpublished analysis by Karsten Grunewald and his team; Supp. Fig. S11). Similarly, the two younger U-Th ages obtained within study (3.85 ka and 1.96 ka) also provide evidence of pre-LIA ice cover.

6 Glacier variations and palaeoclimatic implications

The assessment of complex global patterns in Holocene glacier fluctuations shows that they are influenced by multiple climatic mechanisms and that individual glaciers may not respond uniformly to a particular set of climate forcings (Kirkbride and Winkler, 2012; Solomina et al., 2015). In addition, glaciers are also influenced by topographic conditions, as well as their size and flow dynamics (Sugden and John, 1976; Nussbaumer et al., 2011). The Alps has experienced several glacial expansions and recessions during the Holocene (Nussbaumer et al., 2011), with reports that some glaciers were even smaller than today or entirely absent (Leemann and Niessen, 1994; Hormes et al., 2001; Ivy-Ochs et al., 2009; Solomina et al., 2015). On the other hand, certain regions show evidence of unprecedented modern retreat of glaciers beyond their previous Holocene minima (Koerner and Fisher, 2002; Antoniades et al., 2011; Miller et al., 2013).

Current climate near the Triglav Glacier is characterised by rising temperatures in the melting season (Supp. Fig. S6) and a descending trend of the highest seasonal snow elevation (Supp. Fig. S7). If subglacial deposits would indicate its ongoing existence throughout the Holocene, the present retreat of the Triglav Glacier would indicate cold enough regional climate during previous Holocene optima to sustain the glacier, or an additional (presently unknown) forcing component which would have not been important in the past. Exceptionally quick rate of 21st century melting, for example, has been reported also from Barnes Ice Cap in northern Canada (Gilbert et al., 2017).

Local physiographic influences can insulate small glaciers from the warming effects of regional and global climate (Grunewald and Scheithauer, 2010); it has been shown that some small glaciers show a lower sensitivity to climate fluctuations than previously thought (Colucci and Žebre, 2016). The natural resilience of the Triglav Glacier is due to its relatively high elevation, bright limestone substrate with higher albedo, and the vertical water drainage through karstified rocks and the consequent lack of subglacial lakes as heat collectors (Grunewald and Scheithauer, 2010; Gabrovec et al., 2014). Assuming these factors were relatively constant throughout the Holocene, the possible unprecedented retreat may highlight the consequences of direct anthropogenic forcing (Solomina et al., 2015).

7 Further research

The preliminary data shows a high possibility that subglacial carbonate deposits may endue unprecedented retreat of Triglav Glacier in the southeastern Alps, and are thus an important proxy for further research. Several separate lines of additional evidence are worth studying to strengthen the hypothesis:

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A – High resolution U-Th dating targeting primary calcite. Additionally, isolation and geochemical analyses of primary aragonite would contribute the data on primary U concentration in samples (in case all the crystals were primarily aragonite), which can be used to observe U loss in recrystallised crystals. In situ U-series dating by laser-ablation would represent the best approach as the samples (and laminae) are small and the aim is to target different crystal fabrics.

B – use ^{36}Cl nuclide dating method on the limestone hosting the subglacial carbonate deposits to extract the exposure time of the limestone where those carbonate crusts occur (i.e., no glacier cover) and provide additional data whether those areas have not experienced additional exposures during the Holocene Climatic Optimum. The production rate at 2500 m a.s.l. (the altitude of the Triglav Glacier) is considerably fast, which is in advantage for dating young exposures. In addition, calcite and limestone are one of the best mineral/rock systems for ^{36}Cl because they often have low ^{35}Cl abundances, so there is less of uncertainty contributed to the factors that affect thermal neutron production of ^{36}Cl such as water or snow shielding (Fabel and Harbor, 1999; Marrero et al., 2016).

C – The analyses of particulates on the present remnants of ice (and possible ice cores, if a glacier has not disappeared completely) can highlight the existence of a present-day input to accelerate melting. For example, black carbon and other mineral dust particles in glaciated regions, which accumulate on the ice, can accelerate the melt of glaciers by reducing the albedo (Ramanathan and Carmichael, 2008; Ming et al., 2013; Gabbi et al., 2015). Despite various published examples of such additional contributions, small glaciers would be the most affected due to their larger surface-to-volume ratios.

D – the numerical data of frost weathering. There is relatively extensive literature concerning chemical denudation of the limestone, but scarce numerical data of frost weathering, and no direct measurements concerning subglacial carbonates. This can be experimentally studied by direct freezing-thawing method with controlled humidity and additional measurements of the type of porosity and pressure gradient (Ducman et al., 2011).

8 Conclusion

U-Th ages of subglacial carbonate with the combination of aragonite and calcite are regarded as maximum ages as aragonite-to-calcite transformation, evident in fabrics, might have occurred in calcite crystals that could have been falsely considered as primary. Nevertheless, three ages of subglacial carbonate deposits exposed by the retreating Triglav Glacier fall within the Last Glacial Maximum and Younger Dryas, which could be the first direct evidence of the Triglav Glacier at that time. The fragility of the deposits strongly suggests the continuous glacier-cover since their deposition throughout all but the most recent part of the Holocene, including the climatic optimum. This defines the subglacial carbonates as a complex, but an important palaeoenvironmental proxy and a research subject for further analyses with great potentials, which may highlight the extraordinary nature of the current global warming.

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Data availability

The live and recent-archive photos of Triglav Glacier observation: http://ktl.zrc-sazu.si/

All visual computer data are included in Supplementary files, raw data will be available on the ZRC SAZU repository after the acceptance of the paper.

Author contributions

ML designed the research, led the study, drafted the manuscript and generated figures. AMP performed petrographic analysis, generated the petrographic figures, contributed the writing and editing of the manuscript. JT, MG, MH, BK, MZ contributed the writing and editing of the manuscript. MP contributed the writing and editing of the manuscript and compiled the monitoring data. NZH performed XRD analysis. JZ performed U-Th analysis and wrote the U-Th methods section of the manuscript. RND performed stable isotope analysis, edited and reviewed the manuscript. MF contributed the writing and editing of the manuscript, overall editing and internal review.

Competing interests

The authors declare that they have no conflict of interest.

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505 **Figure 1: Mount Triglav, the Triglav Glacier and the sampling location of subglacial carbonates relative to the years 1932 (A) and 2017 (B). Close up of an exposure of subglacial carbonate (C). Photo curtesy of (A) Janko Skerlep (© ZRC SAZU Anton Melik Geographical Institute archive), (B) Miha Pavšek and (C) Matej Lipar.**

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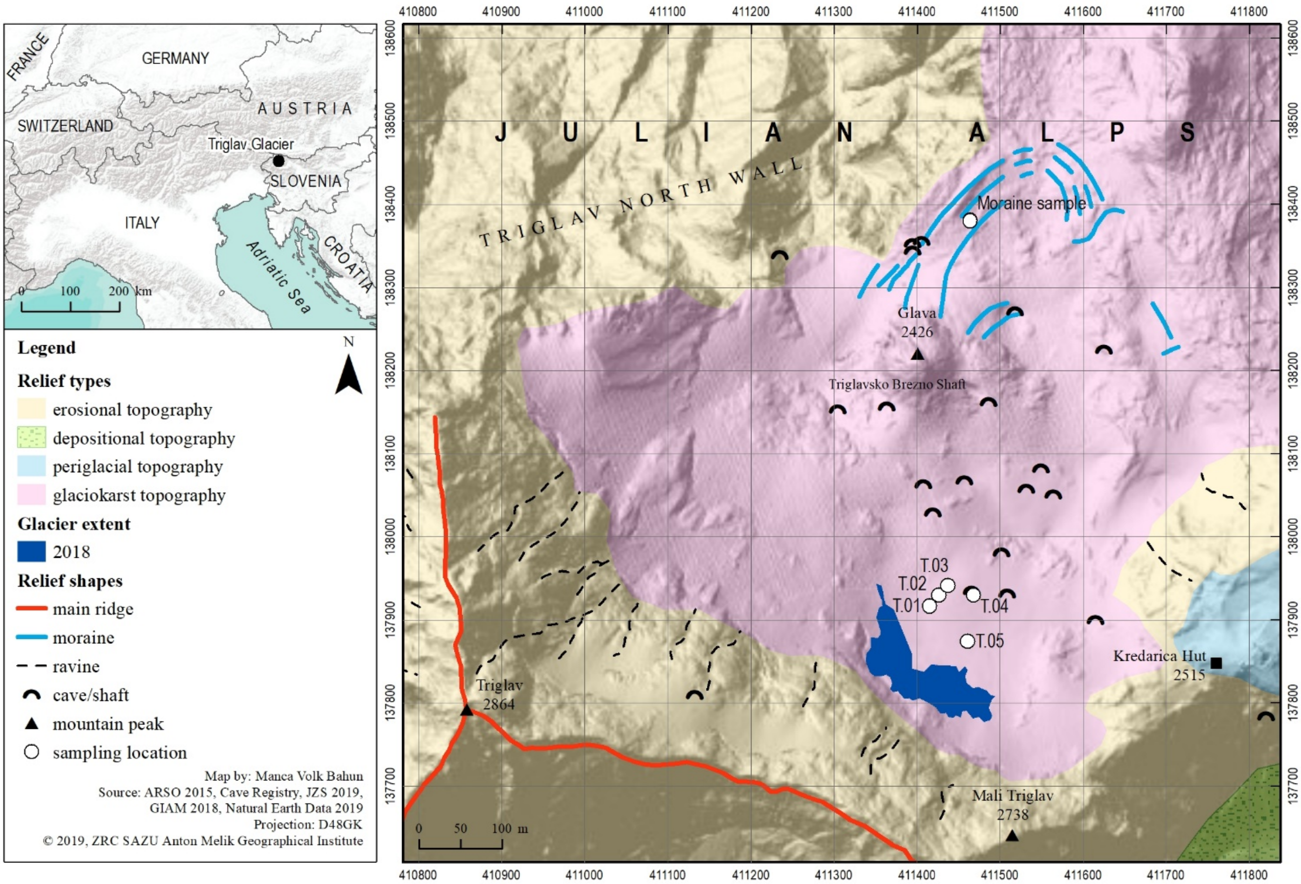

Figure 2: Locality map of the Triglav Glacier, the sampling sites discussed in the text, and general geomorphology.

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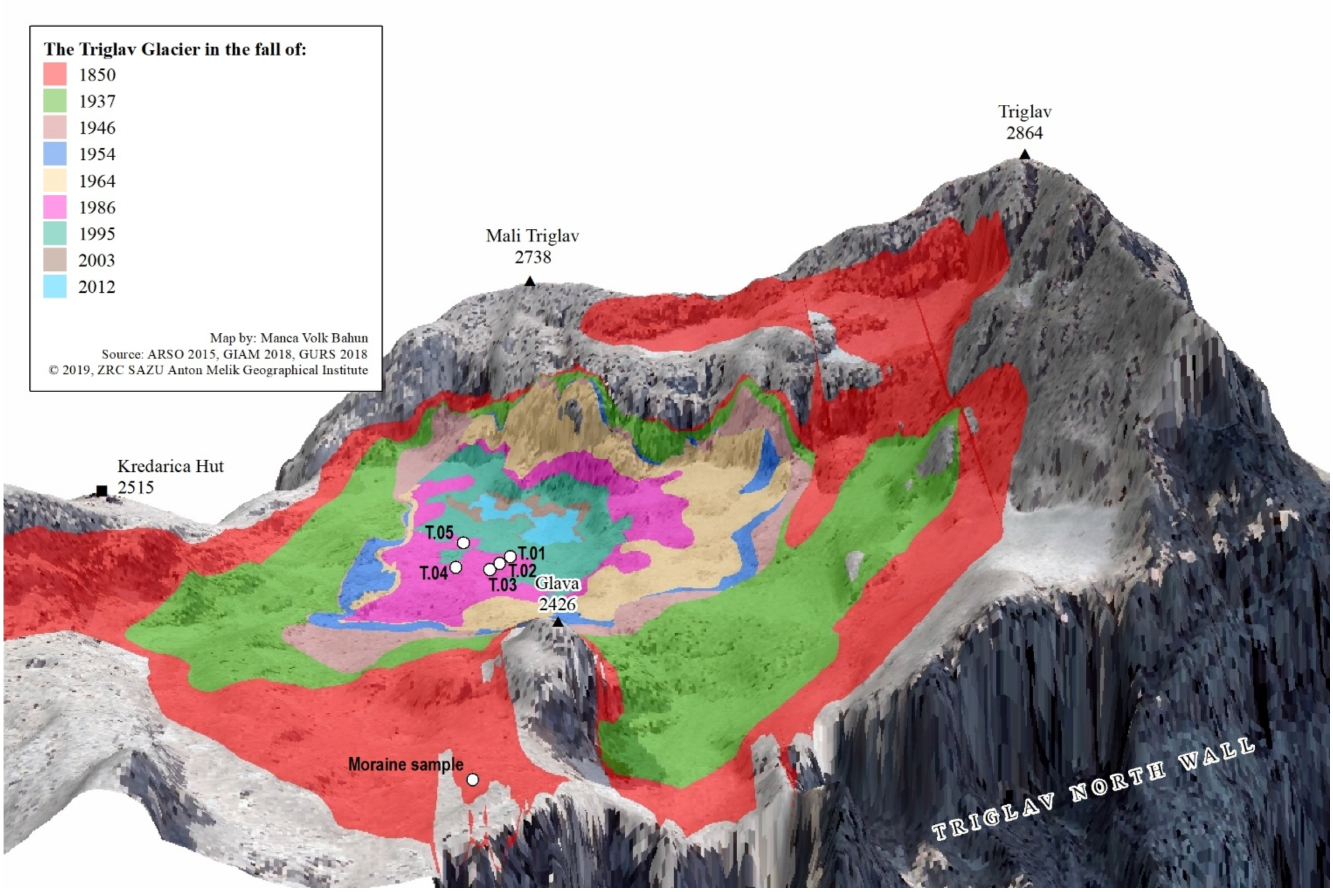

Figure 3: Generated 3D map of the Triglav Glacier extend and the sampling sites discussed in the text.

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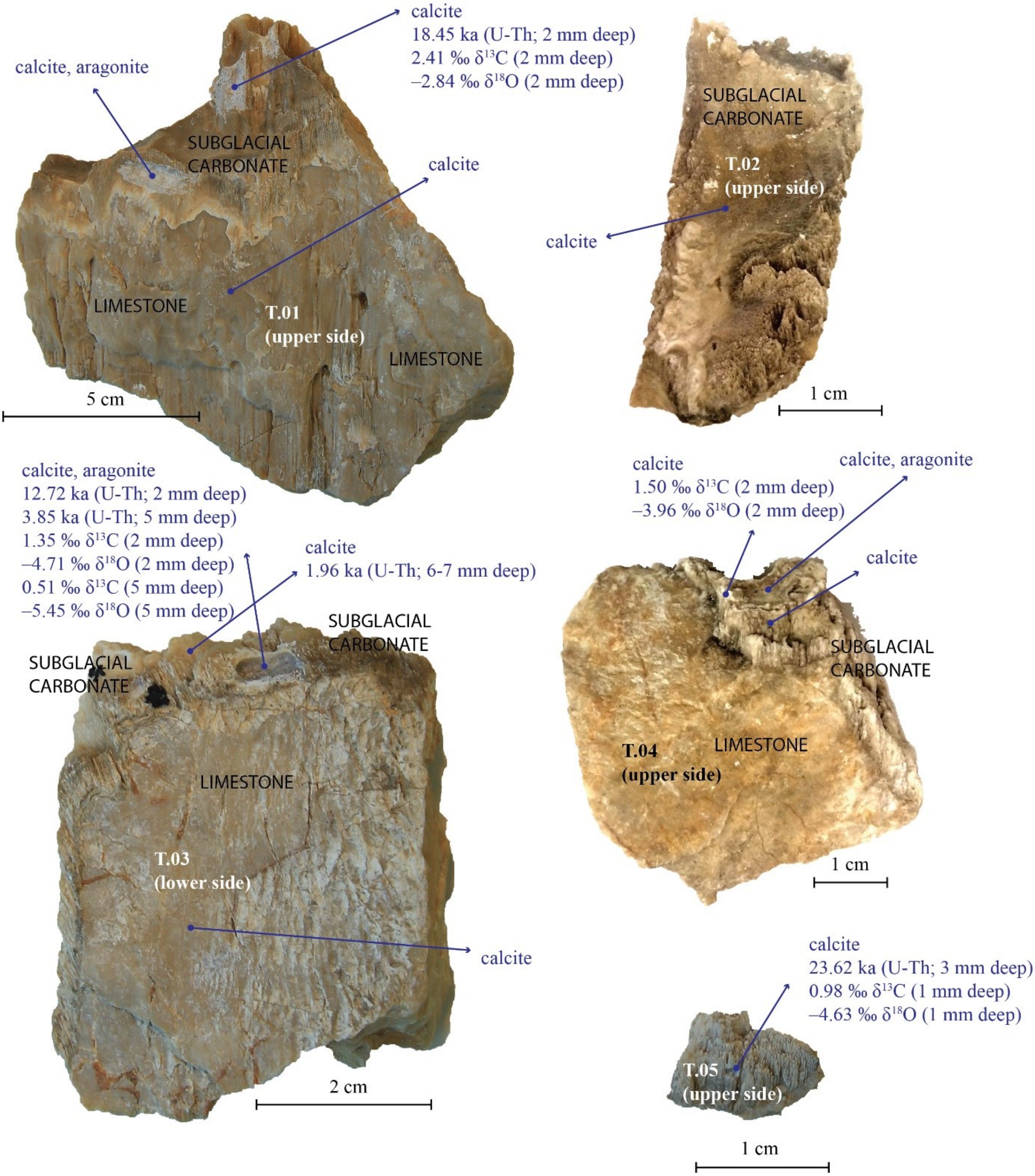

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Figure 4: Subglacial carbonate samples used for this study.

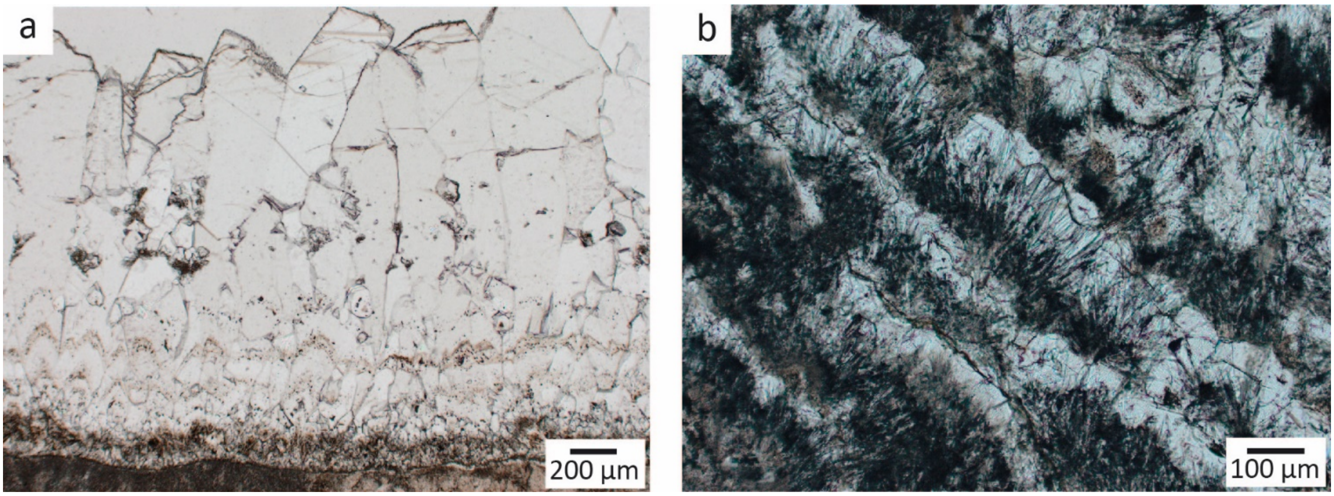

Figure 5: Petrography of the carbonate crusts. a) Primary columnar calcite crystals growing perpendicularly to the substrate on the lee side of the bedrock irregularity.; b) alternation of aragonite (fibrous) and calcite crystals forming layered textures. The base of the aragonite fans of crystals nucleates in dark micritic aggregates. Both images taken under plane polarised light.

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Surface denudation in karst areas (mm/a)			
Location / Source	**From**	**To**	**Precipitation (mm)**
Dachstein, Austria, 1700 – 1800 m a.s.l. (Bauer, 1964)	0.015	0.020	1500
Malham area, NW England, 400 – 500 m a.s.l. (Sweeting, 1964)	0.040	/	1500
Western Julian Alps, 2000 – 2100 m a.s.l. (Kunaver, 1978)	0.094	/	3500
Average for Slovenia, 0 – 2864 m a.s.l. (Gams, 2004)	0.020	0.100	< 900 – > 3200
Northern Calcareous Alps, Austria, 1500 – 2277 m a.s.l. (Plan, 2005)	0.011	0.048	1377
Classical Karst area and Istrian Karst, 0 – 440 m a.s.l. (Furlani et al., 2009)	0.009	0.140	1015 - 1341
Tietar Valley, central Spain, 427 m a.s. l. (Krklec et al., 2016)	0.018	0.025	797
			Average (rounded)
Min	0.009	0.020	**0.01**
Avg	0.0296	0.0666	**0.05**
Max	0.094	0.140	**0.1**

Calculation of subglacial carbonate existance

Thickness (mm)	Existence - max (years)	Existence - avg (years)	Existence - min (years)
0.1	10	2	1
0.2	20	4	2
0.3	30	6	3
0.4	40	8	4
0.5	50	10	5
1	100	20	10
1.5	150	30	15
2	200	40	20
2.5	250	50	25
3	300	60	30
4	400	80	40
5	500	100	50

Table 1: Calculation of subglacial carbonate existence under meteoric environment based on its thickness, years of exposure and denudation rate.