Rock glaciers and mountain hydrology: A review

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Abstract.

In mountainous regions, climate change threatens cryospheric water resources, and understanding all components of the hydrological cycle is necessary for effective water resource management. Rock glaciers are climatically more resilient than glaciers and contain potentially hydrologically valuable ice volumes, and yet have received less attention, even though rock glacier hydrological importance may increase under future climate warming. In synthesising data from a range of global studies, we provide the first comprehensive evaluation of the hydrological role played by rock glaciers. We evaluate hydrological significance over a range of temporal and spatial scales, alongside the complex multiple hydrological processes with which rock glaciers can interact diurnally, seasonally, annually, decadally and both at local and regional extents. We report that although no global-extent, complete inventory for rock glaciers exists currently, recent research efforts have greatly elaborated spatial coverage. Using these research papers, we synthesise information on rock glacier spatial distribution, morphometric characteristics, surface and subsurface features, ice-storage and hydrological flow dynamics, water chemistry, and future resilience, from which we provide the first comprehensive evaluation of their hydrological contribution. We identify and discuss long-, intermediate- and short-term timescales for rock glacier storage, allowing a more balanced assessment of the contrasting perspectives regarding the relative significance of rock glacier-derived hydrological contributions compared to other water sources. We show that further empirical observations are required to gain a deeper hydrological understanding of rock glaciers, in terms of (i) their genesis and geomorphological dynamics (ii) total ice/water volume; (iii) water discharge; and (iv) water quality. Lastly, we hypothesise that at decadal and longer timescales, under future climate warming, degradation of ice within rock glaciers may represent an increasing hydrological contribution to downstream regions, and thus increased hydrological significance while rock glacier water stores persist.

Keywords:
Rock glaciers; Mountain cryosphere; Water storage; Water resources; Climate change; Mountain hydrology

1. Introduction

Glacierised high mountain systems worldwide form natural 'water towers' that constitute a significant freshwater source for downstream regions, particularly in arid and semiarid zones (Messerli et al., 2004; Viviroli et al., 2007). Here, glacial- and snowpack-derived meltwaters buffer hydrological seasonality, contributing to streamflow in otherwise low-flow conditions during drier months (e.g., Kaser et al., 2010). In this context, the mountain cryosphere (snow, ice and permafrost) is important for ecosystem services provision (Grêt-Regamey et al., 2012), supplying multiple societal needs within mountains and the surrounding lowlands – potable water supplies, energy generation (hydropower) and agriculture, for example (Immerzeel et al., 2010; Viviroli et al., 2011). In vulnerable drought-prone regions particularly, glaciers represent an important drought-resilient water source (Bolch, 2017). This has been illustrated for several high-altitude cities located in the Andes (Wouter et al., 2017; Table 1).

Table 1. Relative contribution of glacial melt (%) to the water supply of selected cities under different meteorological conditions. Values in square brackets indicate the uncertainty ranges of the estimates. After Wouter et al. (2017).

	Quito (Ecuador)	La Paz (Bolivia)	Huaraz (Peru)
Annual average (normal year)	2.2 [0.9–5.0]	14.8 [5.9–26.8]	19.0 [7.5–35.4]
Monthly maximum (normal year)	5.3 [2.3–11.1]	61.1 [37.8–77.1]	67.3 [41.9–82.8]
Annual average (drought year)	3.7 [1.5–8.0]	15.9 [6.4–29.4]	27.2 [11.6–46.7]
Monthly maximum (drought year)	15.4 [7.3–27.6]	85.7 [74.1–91.5]	91.1 [78.1–96.0]

The rapid near-global retreat of mountain glaciers, predominantly attributed to anthropogenic causes (Marzeion et al., 2014), has previously been reported (Gardner et al., 2013) and glacial retreat and mass loss is projected to continue throughout the twenty-first century (Marzeion et al., 2012; Radić et al., 2014; Huss and Hock, 2015). Furthermore, under high-end climate change scenarios (RCP8.5) Shannon et al. (2019) project global ensemble mean glacier volume loss to be -64 ± 5% (excluding glaciers situated on the periphery of the Antarctic ice sheet) towards the end of the century, with particular regions experiencing mass losses exceeding 75%, including Central Europe, Caucasus, High Mountain Asia and Southern Andes. Even under conservative projections – limiting global warming to 1.5°C above pre-industrial levels (Paris Agreement) – substantial glacier mass loss occurs; e.g., ~36% reductions in glacier mass by 2100 in High Mountain Asia (Kraaijenbrink et al., 2017). Elevation-dependent warming, i.e. rates of warming are amplified with increasing elevation, suggests high-altitude environments will likely experience comparatively faster warming rates than those at lower elevations, particularly at low-latitudes (Vuille et al., 2008; Mountain Research Initiative EDW Working Group, 2015). Indeed, within certain low-latitude mountain ranges complete loss of glaciers has already occurred (Rabatel et al., 2013). Therefore, long-term glacial stores are finite (Jansson et al., 2003).

In the short-term, annual water release from long-term glacial storage increases; however, beyond 'peak water' enhanced melt rates are overwhelmed by glacier shrinkage, and projected glacier runoff gradually declines. For example, recent global-scale projections encompassing 56 glacierised macroscale (>5000 km^2) basins suggests that to date (2017) peak water has been reached in 45% of the 56 studied basins, increasing to 78% by 2050 (RCP4.5) (Huss and Hock, 2018). Critically, by 2100 Huss and Hock (2018) report glacier runoff reductions exceeding 10% during at least one month of the melt season for one-third of the studied basins; the largest of which occur in Central Asian and Andean basins. These findings are corroborated across a range of spatial scales (e.g., Baraer et al., 2012; Sorg et al., 2014; Frans et al., 2016; Hanzer et al., 2018). Importantly, accompanying glacier mass loss, the potential occurrence of increased rain-to-snow fraction (Berghuijs et al., 2014), reductions in snow cover extent and/or duration (Brown and Mote, 2009; Bavay et al., 2013; Zhou et al., 2017), seasonal runoff maxima shifts towards earlier in the year (Hanzer et al., 2018; Huss and Hock, 2018) and widespread permafrost degradation (Haeberli, 2013; Biskaborn et al., 2019) will further reduce long-term runoff in snowmelt- and icemelt-dominated basins.

The anticipated effects of the future decline of the mountain cryosphere pose far-reaching challenges for effective freshwater resource management. Several studies have previously summarised and discussed such impacts on anthropogenic and ecologic systems (see Beniston, 2003; Barnett et al., 2005; Bolch et al., 2012; Huss et al., 2017; Milner et al., 2017; Beniston et al., 2018), and we refer interested readers to those manuscripts for details. In terms of climate change adaptation strategies, an understanding of all components of the hydrological cycle in high mountain systems is vital (Jones et al., 2018a). However, whilst much has been written on the hydrological role of debris-free glaciers (see Fountain and Walder, 1998; Jansson et al., 2003; Irvine-Fynn et al., 2011) and increasingly on debris-covered glaciers (Fyffe et al., 2019, and references therein), that of rock glaciers has received comparatively less attention (Duguay et al., 2015).

Rock glaciers are landforms consisting of a continuous, thick seasonally frozen debris layer (known as the *active layer* [AL]) covering ice-supersaturated debris or pure ice (Berthling, 2011; Bonnaventure and Lamoureux, 2013). They are formed by gravity-driven creep as a consequence of internal ice deformation. Intact rock glaciers (i.e. those features within which ice presence is expected beneath the AL [Barsch, 1996]) are thought to contain ice volumes of significant value (Azócar and Brenning, 2010; Rangecroft et al., 2015; Jones et al., 2018b; Munroe, 2018). Critically, due to the insulating effect of the AL, internal thermal regimes are at least partially decoupled from external micro- and meso-climates in summer (Juliussen and Humlum, 2008; Millar et al., 2013). As a result, rock glaciers are reasonably assumed to have retarded ice melt, which suggests these landforms may prolong long-term water storage in high mountain systems and buffer losses from alternative sources (Millar et al., 2013; Rangecroft et al., 2015; Bosson and Lambiel, 2016; Jones et al., 2018b). Furthermore, rock glacier presence and abundance affects the amount and properties of runoff from high mountain watersheds. The potential hydrological value of rock glaciers, and thus their importance in terms of hydrological research, was first noted by Corte (1976). Yet, despite an acceleration of rock glacier-related research during recent decades – searches within Scopus® using 'Article title, Abstract, Keywords' for all spelling variants of *rock glacier(s)* generated 973 peer-reviewed articles and reviews to date[(1)], 390 (40%) of which have been published since 2010 – research focusing upon their hydrological role remains limited. For example, Duguay et al. (2015) report that searches of both ISI Web of Science™ and Geobase™ resulted in just 28 papers with an appropriate discussion on rock glacier hydrology. Therefore, despite the near-ubiquitous nature of rock glaciers in high mountain systems (Jones et al., 2018a), there remains a need to understand the state-of-knowledge regarding the hydrological role of rock glaciers. The rationale and aim of this manuscript is thus to describe the state of current scientific knowledge about the hydrological role and contribution of rock glaciers in mountain regions and to signpost towards critical future directions for rock glacier hydrological research.

2. Rock glaciers

2.1. Rock glacier characteristics

Rock glaciers are lobate or tongue-shaped assemblages of poorly sorted, angular-rock debris and ice (ice-cored or ice-cemented [Section 2.2]) commonly found in high mountain environments, which move as a consequence of the deformation of internal ice (Giardino and Vitek, 1988; Barsch, 1996). Previously, rock glaciers have been classified according to their ice content and dynamic behaviour (Fig. 1); *active rock glaciers* contain ice and display movement, *inactive rock glaciers* contain ice and no longer display movement and *fossil rock glaciers* do not contain ice and no longer move, and are referred to regularly as *relict* (Haeberli, 1985; Barsch, 1996). Importantly, Kääb (2013) notes that "this classification is a theoretical concept. The transition between the three stages is actually continuous".

Active rock glaciers display rates of movement in the order of centimetres to a few decimetres per year (see Table 3 in Janke et al., 2013), although cases have been reported with surface velocities of several metres per year (Gorbunov et al., 1992; Kääb et al., 2003; Delaloye et al., 2013; Sorg et al., 2015; Hartl et al., 2016b; Eriksen et al., 2018). They are characterised by distinctive flow-like morphometric features reflecting their visco-plastic properties; spatially organised longitudinal or transverse ridge-and-furrow assemblages, steep (~>30–35°) and sharp-crested front and lateral slopes that typically rise 15–70 m above adjacent terrain, light-coloured (i.e. little weathered) frontal slope in contrast to the dark-coloured rock-varnished (i.e. greatly weathered) uppermost surface, a swollen, noticeably longitudinally convex appearance of the rock glacier body, and an absence of vegetation and/or lichen cover (Wahrhaftig and Cox, 1959; Martin and Whalley, 1987; Baroni et al., 2004; Haeberli et al., 2006; Harrison et al., 2008).

Inactive rock glaciers still contain ice but are immobile. Two types of inactivity can be defined: *climatically inactive*, where the ice has melted; and *dynamically inactive* where there is reduced nourishment of talus and/or ice as the rock glacier extends too far from the headwall (e.g., Kellerer-Pirklbauer and Rieckh, 2016), are cited as possible causes for this behaviour (see Barsch, 1996, p. 8–10). In comparison to active rock glaciers, the surface micro-topography of inactive features is relatively subdued. They generally have

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gentler, dark-coloured rock-varnished frontal slopes with partial to full vegetation and/or lichen cover (Ikeda and Matsuoka, 2002). As a consequence of the difficulty of differentiating between active and inactive forms, particularly through photogeomorphology, active and inactive rock glaciers are often collectively termed *intact*.

Relict rock glaciers, defined as former rock glaciers, no longer contain any ice and are characterised by subdued surface micro–topography. They often exhibit surface collapse features including thermokarst ponds, i.e. water-filled depressions resulting from melting of stagnant glacial ice, and have gentler (~<30°) and round-crested front and lateral slopes, a dark-coloured rock-varnished frontal slope, and extensive vegetation and/or lichen cover (Martin and Whalley, 1987; Barsch, 1996; Baroni et al., 2004; Harrison et al., 2008).

Fig. 1. Typical examples of active [a, b], inactive [c, d] and relict [e, f] rock glaciers from around the world: (a) Sourdough rock glacier, Wrangell Mountains, AK, USA (61°23'N, 142°44'W). Note the steep headwall that serves as a source of snow avalanches and rockfall; (b) Caquella rock glacier, Bolivian Andes of South Lipez, Bolivia (21°29'S, 67°55'W); (c) Liapey d'Enfer rock glacier, Hérens valley, Swiss Alps, Switzerland (46°05'N, 7°32'E); (d) rock glaciers in the Niggelingtälli, Turtmann Valley, Swiss Alps, Switzerland (46°13'N, 7°45'E); (e) Hoelltal rock glacier, Niedere Tauern

Range, Central Eastern Alps, Austria (47°22'N, 14°39'E); and (f) rock glaciers beneath Le Mourin mountain, Valais, Swiss Alps, Switzerland (45°56'N, 7°10'E). On the photographs, dashed lines correspond to the approximate rock glacier boundary. Images [a] modified after Anderson et al. (2018) and [b–f] from Google Earth.

It is important to note that recognition, delineation and classification (in terms of their activity) is not a trivial undertaking both from *in situ* surveys, or from analysis of remote sensing/photographic data, particularly where: (i) the "characteristic" surface morphology is not evident (Whalley et al., 1986), and/or (ii) rock glaciers form multi-lobed complexes with lobes of different activity types superimposed and embedded onto/into one another, forming a cascading form with active lobes at higher elevations and relict lobes at lower elevations (Roer and Nyenhuis, 2007). Regardless, identifying and establishing the activity status of rock glaciers represents an important initial step in determining their potential hydrological significance.

2.2. Rock glacier origin and evolution

A long-standing academic debate regarding rock glacier origin pervades the literature (see Barsch, 1977, 1987, 1996; Whalley and Martin, 1992; Hamilton and Whalley, 1995; Clark et al., 1998; Whalley and Azizi, 2003; Haeberli et al., 2006; Berthling, 2011). Specifically, the rock glacier controversy can be framed as the permafrost model where internal ice is assumed to be of a dominantly periglacial/permafrost origin (Haeberli, 1985) vs. the glacier ice core model where a dominant glacial origin is assumed. In reality, within deglacierising mountains rock glaciers are equifinal inasmuch as they can arise from separate or combined periglacial, glacial and paraglacial (i.e. landscape relaxation) processes (Knight et al., 2019). Indeed, glaciological vs. slope vs. climatic controls on the evolution of rock glaciers may vary through the rock glacier life cycle (ibid.). Here, we do not seek to contribute to this debate (this is beyond the scope of this paper) – several papers have already discussed the arguments for and against the different positions (see Whalley and Martin, 1992; Barsch, 1996; Haeberli et al., 2006; Berthling, 2011, for reviews); rather, we adopt the dispassionate view that rock glaciers can be derived through either model (as per Berthling, 2011) and proceed to describe these hypotheses in further detail below.

The permafrost model for rock glacier genesis follows Wahrhaftig and Cox (1959) where interstitial ice (pore-ice) or segregated ice (ice lenses), primarily derived from either the freezing of rain and meltwater percolating through the rock glacier matrix, the freezing of groundwater, and/or the burial of snow and ice accumulations (Burger et al., 1999; Haeberli, 2000; Haeberli et al., 2006), produces creep (Wahrhaftig and Cox, 1959; Barsch, 1977, 1987, 1988, 1996; Haeberli, 1985). Rock glaciers of periglacial origin are often called *talus-derived rock glaciers* (Humlum, 1996) or *ice-cemented rock glaciers* (Wayne, 1981). Of note is the occurrence of rock glaciers in nonglacial, periglacial environments, therefore past or present glaciation is not a prerequisite for their formation (Haeberli, 1985; Giardino and Vitek, 1988; Hamilton and Whalley, 1995). Proponents of this model suggest that little evidence exists to support the glacier ice core model (see Berthling, 2011, for detailed discussion), although they acknowledge the possibility of incorporation of glacier (sedimentary) ice in permafrost (e.g., Haeberli, 1989; Haeberli and Vonder Mühll, 1996; Kääb et al., 1997; Haeberli et al., 2006). In such cases it is argued that the long-term existence of these rock glaciers requires permafrost conditions (Harris and Murton, 2005; Berthling, 2011; Kääb, 2013).

Based on *in situ* data, other authors have presented evidence that supports a glacigenic origin (i.e. glacier ice core model) for certain rock glaciers (Outcalt and Benedict, 1965; Potter, 1972; Whalley, 1974; White, 1976; Whalley et al., 1994; Humlum, 1996; Potter et al., 1998; Ishikawa et al., 2001; Monnier et al., 2013; Petersen et al., 2016; Guglielmin et al., 2018). This model involves the creep of a thin (typically <50 m) ice body, which has been buried and preserved by an insulating weathered rock debris layer (Whalley and Martin, 1992; Whalley and Azizi, 2003). Recently, Anderson et al. (2018) showed that rock glaciers of glacigenic origin represent a plausible end-member response that is captured in numerical models of debris-free glaciers. Rock glaciers of this type are also referred to as *moraine-derived rock glaciers* (Harrison et al., 2008), *ice-cored rock glaciers* (Potter, 1972), *glacier ice-cored rock glaciers* (Johnson, 1978) or *glacier-derived rock glaciers* (Humlum, 1996). Figure 2 represents a simplified perspective of rock glacier composition for features derived from either the permafrost or glacier ice core model as outlined by Martin and Whalley (1987).

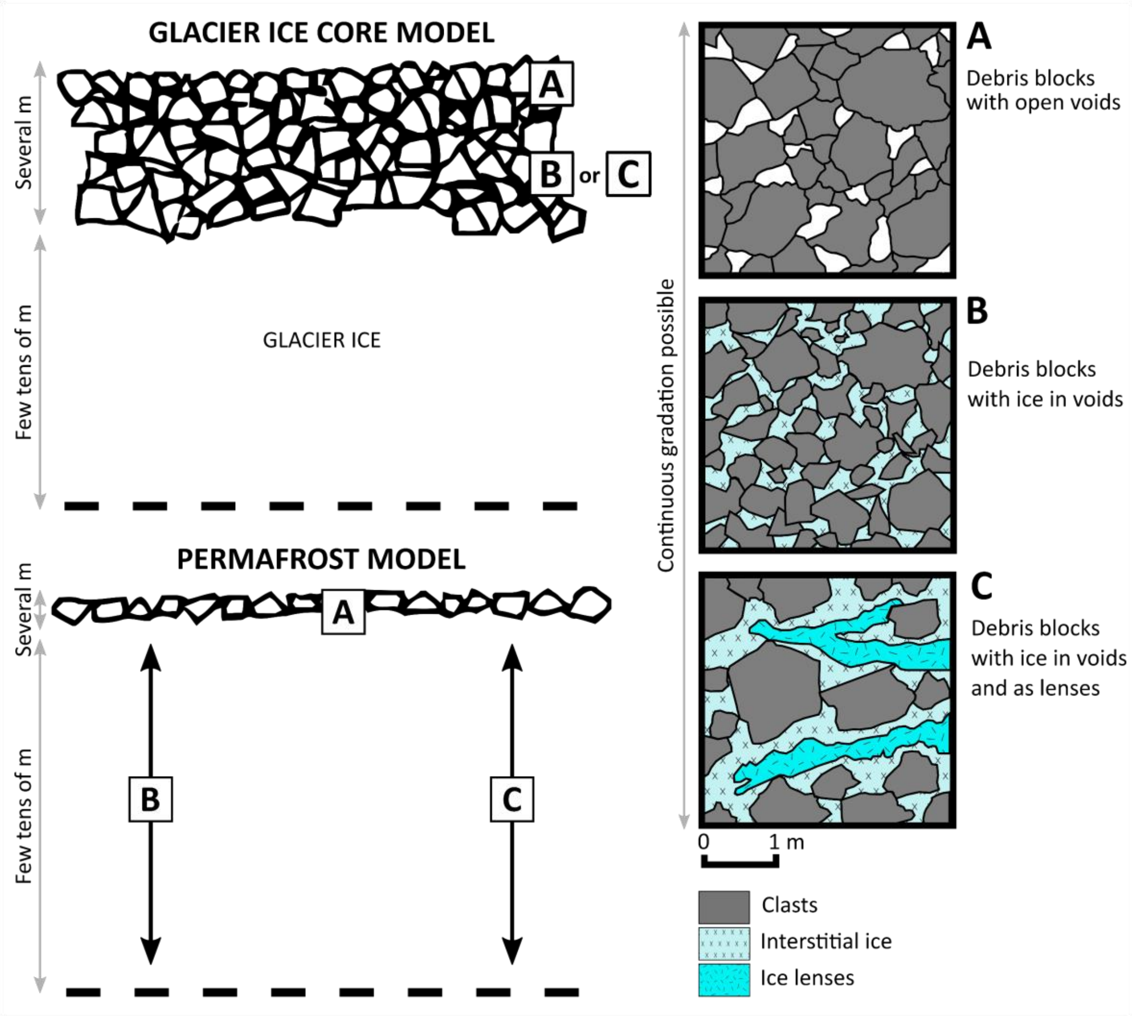

Fig. 2. Basic representation of rock glacier internal composition associated with the glacier ice-core and permafrost models. Modified after Martin and Whalley (1987).

Proponents of the two competing concepts of rock glacier formation generally focus on already well-developed landforms (Monnier and Kinnard, 2015b). Yet, there are striking examples of large glacier-rock glacier composite features where the lowermost parts of debris-covered glaciers are *currently developing* into rock glaciers. Cases of glacier-to-rock glacier transition within relatively short timescales have been reported; for example, within ca. 50 years at Sachen Glacier, Nanga Parbat, Pakistan (Shroder et al., 2000) and ca. 60 years at Presenteseracae debris-covered glacier, central Andes, Chile (Monnier and Kinnard, 2015b). Nevertheless, studies of glacier-rock glacier interactions are rarely orientated towards such examples (Monnier and Kinnard, 2015b), in spite of their potential to elucidate the drivers behind which glaciers will fully transition into rock glaciers and those which will simply downwaste.

Here, it is important to distinguish between rock glaciers (cf. Section 2.1) and debris-covered glaciers (Hambrey et al., 2008; Benn and Evans, 2010; Cogley et al., 2011; Jiskoot, 2011; Kirkbride, 2011), particularly when reviewing the hydrological significance of the former; grouping these features would incorrectly inflate the hydrological significance of rock glaciers. Debris-covered glaciers are glaciers in which the ablation zone is partly or wholly covered with thin (typically less than several-decimetres thick) supraglacial debris (Kirkbride, 2011). There are critical differences between rock glaciers and debris-covered glaciers : rock glacier movement is governed by internal deformation, the majority of which occurs in a shear zone at depth within the feature (Arenson et al., 2002; Buchli et al., 2013, 2018; Krainer et al., 2015; Kenner et al., 2017a); debris-covered glacier motion may occur due to internal deformation, basal sliding, and soft bed deformation. Importantly, basal sliding is generally non-occurring or very limited for cold-based debris-covered glaciers (i.e. glaciers frozen to their beds), and only debris-covered glaciers underlain by a soft deformable substrate (i.e. unlithified sediments or poorly consolidated sedimentary rocks) exhibit soft bed deformation. The surface of debris-covered glaciers is complex topographically, consisting of a spatially-chaotic mosaic of features such as hummocks, depressions, supraglacial melt ponds and ice cliffs; the surficial instability and discontinuity of the debris-covered glacier debris layer mean that such ice exposures are frequently visible. Contrastingly, rock glacier surfaces are characterised by spatially coherent flow-like topography (Section 2.1) and surficial ice-exposures are infrequent.

Monnier and Kinnard (2017) identify three types of glacier-rock glacier dynamic relationships within the literature: (i) the re-advance of glaciers or debris-covered glaciers overriding older permafrost bodies and coalescing (Lugon et al., 2004; Haeberli, 2005; Ribolini et al., 2007, 2010; Monnier et al., 2013; Dusik et al., 2015; Bosson and Lambiel, 2016; Kellerer-Pirklbauer and Kaufmann, 2018; Kenner, 2019). Such glacier-rock glacier interactions are defined by the permafrost model; (ii) the continuous emergence of a rock glacier from a debris-covered glacier, as indicated by the evolution of the surface morphology, together with the creep of a massive and continuous ice body that has been buried and preserved (Potter, 1972; Potter et al., 1998; Humlum, 2000; Krainer and Mostler, 2000). These types of glacier-rock glacier interactions are described by the glacier ice core model; (iii) debris-covered glacier-to-rock glacier transition through the evolution of the surface morphology and the internal structure, i.e. the development of a perennially frozen ice-rock mixture resulting from the incorporation of surface-derived debris and periglacial ice and fragmentation of the initial massive and continuous ice body (Monnier and Kinnard, 2015b, 2017; Seppi et al., 2015). Monnier and Kinnard (2015b) describe this as an alternative to the dichotomous debate between a periglacial or glacial origin. Regarding (ii) and (iii), the emerging rock glacier and debris-covered glacier morphology are in complete continuity, suggesting a continuum between debris-free glaciers and rock glaciers where debris-covered glaciers form an intermediate stage (Giardino and Vitek, 1988; Ackert, 1998).

With continued climate-driven deglaciation, high mountain systems are transitioning from glacial to paraglacial dominated process regimes (Harrison, 2009). Ballantyne et al. (2014) note that formerly glacierised high mountain systems "are characterised by a high spatial density of large-scale post-glacial rock-slope failures (RSFs) such as major rockfalls, rockslides, rock avalanches and deep-seated gravitational slope deformations". RSFs occur in response to debuttressing or deglacial unloading that follows the exposure of glacially steepened rockwalls by glacier downwastage and retreat (Ballantyne, 2002; Fischer et al., 2006). In the context of current and future climatic conditions, enhanced paraglacial processes (i.e. RSFs) driven by continuing deglaciation could increase supraglacial debris accumulation upon glacial forms, and thus limit ablation of the underlying ice (Section 3) (Lambrecht et al., 2011; Pellicciotti et al., 2014; Lardeux et al., 2016). Thick supraglacial debris cover (i.e. decimetres to metres) influences glacier dynamics significantly, as inefficient sediment evacuation processes encourage glacier-rock glacier interactions (Shroder et al., 2000). Recent numerical model simulations report that under significant warming (+2.5°C) debris-covered glacier-to-rock glacier transition can occur rapidly (~100 years) (Anderson et al., 2018). Therefore, glacier-rock glacier interactions could enhance the resilience of the mountain cryosphere, preserving frozen water stores as glaciers transition to rock glacier forms. Importantly, however, these landform assemblages are not included in glacio-hydrological modelling, which usually focuses solely on glaciers (Bolch et al., 2019, and references therein). As such, an improved understanding of glacier-rock glacier dynamic relationships is critically important in the context of future water resources management. We further argue that of particular importance are empirical studies that seek to elucidate the drivers behind which glaciers will fully transition into rock glaciers and those which will simply downwaste.

2.3. Rock glacier water storage

Rock glacier water storage occurs as ice, snow and water at *long-term*, *intermediate-term* and *short-term* timescales (Jones et al., 2018b; Fig. 3), similar to glacier storage (cf. Jansson et al., 2003). Long-term storage concerns ice storage below the AL of rock glaciers on multi-annual to centennial and millennial timescales (e.g., Clark et al., 1996; Krainer et al., 2015). Recent research concludes that rock glaciers constitute non-negligible long-term water stores, particularly in deglacierising/deglacierised semi-arid and arid regions (Section 4). In addition, this storage also includes the release of these water stores through degradation of the internal ice body. Intermediate-term storage encompasses the storage and release of snowmelt and AL thaw-derived runoff on a seasonal timescale (Section 5). Short-term storage includes diurnal drainage of en- and sub[rock]glacial water through the rock glacier (Section 5). In this context, intermediate-term and short-term storage can strongly influence catchment runoff characteristics, especially in catchments where rock glaciers are more abundant than glaciers. In addition, event storage and releases (i.e. singular storage releases), which have irregular occurrences and/or irregular intervals, are also types of rock glacier storage; for example, intermittent thermokarst ponds (Giardino et al., 1992; Haeberli et al., 2001; Kääb and Haeberli, 2001) or rock glacier-dammed lakes formed as a consequence of river channel disruption (Hewitt, 2014; Rosenwinkel, 2018; Blöthe et al., 2019). Detailed knowledge of the timescales and forms of rock glacier water storage represents critical information for the management of such resources but is currently lacking.

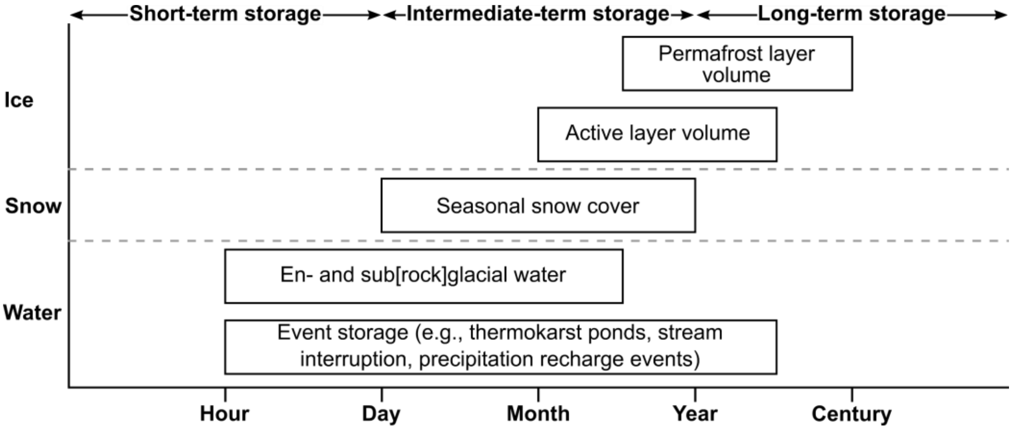

Fig. 3. Schematic diagram showing the different forms of rock glacier storage and their associated timescales. Modified after Jones et al. (2018b).

3. Ice preservation

Active rock glacier internal structure consists of two basic units: firstly, the AL, which is typically a few decimetres to a few metres in thickness and secondly, underlying the AL, a core of ice-supersaturated debris (i.e. nonglacial) or pure ice (i.e. glacial) (Ballantyne, 2018, p. 243). The AL typically comprises coarse blocky clasts ~0.2–5.0 m in length (Humlum, 1997) (Fig. 4a), although boulders exceeding 5 m in length are sometimes present (Fig. 4b).

Fig. 4. Ground-based views of the lowermost part of the Chola Glacier (Khumbu Himal, Nepalese Himalaya, May 2017), an ongoing glacier-rock glacier interaction, including: (a) the coarse-blocky openwork debris that is characteristic of rock glacier AL surfaces. Field sampling of the visible clasts suggests mean grain size ~1.9 m (b-axis); and (b) the variability of grain size (i.e. >5 m blocks) visible at rock glacier surfaces. The grain size variability reflects the diversity of

processes (e.g., rockfalls, snow avalanches etc.) by which debris is transferred to the rock glacier surface (Haeberli et al., 2006). Researcher for scale. Photos: Darren B. Jones.

Complex internal thermal regimes are generated within the coarse-blocky openwork structure of the AL, such that the AL acts as a thermal filter between the surface energy balance and the subjacent frozen rock glacier core (Humlum, 1997; Hanson and Hoelzle, 2004). Indeed, Gruber and Hoelzle (2008) illustrate that both the temperature beneath the seasonal snow cover and mean annual ground temperatures at greater depth can be considerably reduced due solely to the low thermal conductivity of the openwork blocky debris according to a simple and purely conductive model. Consequently, the thermal regime within coarse-blocky openwork debris is different to the surrounding environment leading to the development of cooler ground temperatures when compared to fine-grained or bedrock surfaces in similar settings (Harris and Pedersen, 1998; Juliussen and Humlum, 2008) and mean annual air temperatures (MAATs) (Gorbunov et al., 2004; Millar et al., 2013). This leads to the continued persistence of buried ice at elevations where MAAT exceeds 0°C, i.e. elevations where permafrost persistence outside of rock glaciers and similar landforms is highly improbable (e.g., Baroni et al., 2004; Popescu et al., 2017), occasionally reaching below the tree line (e.g., Sorg et al., 2015; Charbonneau and Smith, 2018) (Fig. 1a).

It is probable that a number of non-conductive (i.e. convective and advective heat flow) and conductive processes are responsible for the cooling influence of openwork blocky debris in relation to rock glaciers, talus slopes and blockfields (Harris and Pedersen, 1998). These processes include: (i) the Balch effect; (ii) the chimney effect; (iii) continuous air exchange with the atmosphere; (iv) summer-time evaporation or sublimation of water and/or ice; and (v) conductive heat loss via boulder protrusion. At different times of the year all of these mechanisms could feasibly be operating, but under different circumstances governed by the duration, depth and permeability of seasonal snow cover, local topography (i.e. slope length and gradient) and openwork blocky debris thickness (Ballantyne, 2018, p. 51). Each is summarised below.

(i) *The Balch effect (or Balch ventilation).* This is defined as the insulating effect of air-filled voids within the openwork blocky debris (Thompson, 1962; Barsch, 1996, p. 238). During periods of low wind speeds and no or little snow cover, density-induced cooling occurs as comparatively cold air masses penetrate the openwork blocky debris and displace warmer air masses. In contrast to this, warmer air masses at the surface are prevented from penetrating into the openwork blocky debris by cold air trapped within inter-clast voids. Consequently, heat transfer is conductive only, thus warming of the openwork blocky debris at depth is sluggish, whereas density-induced non-convective processes (e.g., Balch ventilation) take place much more rapidly, particularly at night (e.g., Humlum, 1997). Importantly, wind pumping produced by high winds, however, may upset the above-described pattern and even dynamically displace trapped cold air as comparatively warmer and less dense near-surface air masses are driven into the openwork blocky debris by means of forced ventilation (Humlum, 1997). Of note, Ballantyne (2018, p. 50) n that most investigators reject this explanation of negative temperature anomalies within openwork blocky debris as it fails to explain seasonal temperature variations at depth.

(ii) *The chimney effect.* First proposed by von Wakonigg (1996), this theory concerns a seasonally switching air circulation mechanism that produces ascending warm air in winter and descending cold air in summer. Consequently, a positive and negative thermal anomaly develops in the upper and lower parts of the slope, respectively. Specifically, in winter, warmer air masses move upslope through the openwork blocky debris under thick seasonal snow cover, exiting through warm funnels in the upper parts of the slope. As a result, the concomitant aspiration of cold air into the lower parts of the slope occurs. This process is most efficient during particularly cold periods leading to the build-up of a cold reservoir in the lower parts of the slope. In summer, this mechanism is reversed, with a gravity discharge of cold air through the openwork blocky debris, exiting at the foot of the slope (Harris and Pedersen, 1998; Delaloye and Lambiel, 2005). This process is frequently perceptible as a persistent breeze towards the base of rock glacier frontal slopes during the summer (Delaloye and Lambiel, 2005). Importantly, the chimney effect, therefore, facilitates the preservation of ice in openwork blocky debris on slopes >1000 m below the regional limit of discontinuous permafrost, where MAAT is >+5°C (Delaloye and Lambiel, 2005). In addition, the results of recent 2-D numerical modelling (cf. Wicky and Huack, 2017) successfully replicate the above-described mechanism, placing further emphasis on its importance for the preservation of frozen ground under future climate warming.

(iii) *Continuous air exchange with the atmosphere.* Proposed by Harris and Pedersen (1998), this theory is a simple extension of the chimney effect (ii) in areas where continuous snow cover is lacking. In its absence, continuous air exchange with the atmosphere occurs over the entirety of the openwork blocky debris occurs; therefore, in response to changes in air temperature, almost instantaneous warming and cooling of the openwork blocky debris to a considerable depth occurs. This process is most effective in windy situations on steep slopes.

(iv) *Summer-time evaporation or sublimation of water and/or ice.* Latent heat absorbed from block surfaces in these processes may cool the blocks in the upper layers of the openwork blocky debris (von Wakonigg, 1996). This process is most effective in regions with relatively dry summer air (Harris and Pedersen, 1998).

(v) *Conductive heat loss via boulder protrusion.* Boulders protruding into and through the seasonal snow cover act as "efficient heat bridges", thermally coupling the openwork blocky debris and the surface air in winter and thereby enhancing conduction (Juliussen and Humlum, 2008). In block fields (Elgåhogna and Sølen Mountains, central-eastern Norway), Juliussen and Humlum (2008) recorded mean annual ground temperatures 1.3–2.0°C lower than nearby till and bedrock.

In addition to the above-described processes, ice subjacent to the AL can 'self-preserve' as it increases the heat capacity, thermal conductivity and emissivity of the ground relative to unfrozen ground within which the pore spaces are air-filled. It may act as an effective heat sink, rapidly absorbing, emitting and distributing heat without undergoing high amounts of melt (Kenner et al., 2017b). Critically, therefore, rock glaciers have retarded melt as the ice underlying the AL is thermally decoupled from external macro- and meso-climates. Indeed, long-term ice preservation is feasible within rock glaciers previously considered morphologically inactive or relict (Section 2.1) (e.g., Scapozza et al., 2011; Harrington et al., 2018; Colucci et al., 2019), as the lower ice content potentially increases AL porosity [and potentially void-interconnectedness], which improves internal air circulation (Delaloye and Lambiel, 2005). For example, field investigations at the inactive Helen Creek rock glacier (Banff National Park, Alberta, Canada) indicate the presence of isolated patches of subsurface ice where the AL is most coarse (clasts often >1 m b-axis) (Harrington et al., 2018). As a consequence, the response of rock glaciers to present-day and future climate warming may occur at comparatively longer timescales than glaciers (Giardino et al., 2011; Kenner and Magnusson, 2017; Anderson et al., 2018; Jones et al., 2018a). Indeed, Janke et al. (2013) note that "[u]nlike glaciers that are sensitive to extreme fluctuations on a shorter timescale, a strong climatic signal must exist to produce change in a rock glacier system". On this basis, it is reasonable to conclude that the hydrological role of rock glaciers (i.e. long-term storage) will likely become increasingly important with continued glacier recession (Bolch and Marchenko, 2006; Millar and Westfall, 2008), at least until the rock glaciers themselves become relict.

Of note, however, are emerging observations of increased rock glacier surface velocities potentially in response to recent climate warming at both decadal (Kääb et al., 2007; Kaufmann and Ladstädter, 2007; Delaloye et al., 2008; Bodin et al., 2009; Scapozza et al., 2014; Nickus et al., 2015; Sorg et al., 2015) and seasonal (Kääb et al., 2003; Perruchoud and Delaloye, 2007; Delaloye et al., 2010; Liu et al., 2013; Wirz et al., 2016) timescales. In the European Alps, for example, annual terrestrial geodetic surveys conducted at 16 rock glacier lobes suggest that relative to the respective previous year, mean surface velocity increase was ~+52% during the reporting period (2010–2014) with most rock glaciers reaching new surface velocity maxima in 2014 (PERMOS, 2016). Elsewhere, striking examples of rapid rock glacier movement (i.e. several metres annually) (Delaloye et al., 2013; Hartl et al., 2016b; Eriksen et al., 2018) and partial rock glacier collapse (Bodin et al., 2017) have been explained, at least in part, by climatic factors. Furthermore, the synchronous kinematic behaviour recorded at multiple rock glaciers with considerably different local conditions (e.g., elevation, topographical conditions, lithology), has been attributed to external drivers (i.e. climate warming) (Kääb et al., 2007; Delaloye et al., 2008, 2010; Kellerer-Pirklbauer and Kaufmann, 2012; Sorg et al., 2015; Kellerer-Pirklbauer et al., 2018). In explanation, increased rock glacier surface velocities are potentially due to modification of the rheological behaviour of warming ice (i.e. increased internal deformation) (Kääb et al., 2007) and/or hydrological effects (i.e. increased water content) within the frozen rock glacier core (i.e. higher pore pressure) or at the base (i.e. possibly basal sliding) (Ikeda et al., 2008; Roer et al., 2008; Buchli et al., 2013, 2018; Kenner et al., 2017a).

Rock glaciers with ground temperatures close to 0°C are reported to have a higher thermal responsiveness and creep faster in general than colder features (Kääb et al., 2007; Müller et al., 2016), and thus are likely to be more vulnerable to future climate warming. Numerical flow modelling of the Huhh1 and Murtèl rock glaciers (Swiss Alps, Switzerland) by Müller et al. (2016) indicate that an immediate 1°C increase in rock glacier temperature considerably affects rock glacier horizontal velocity and surface geometry (Fig. 5) – features with temperatures closest to 0°C are most impacted. Further, Marcer et al. (2019) modelled the destabilisation susceptibility of rock glaciers (see section 'Reaction Typology' in Schoeneich et al., 2015), reporting that occurrence of this phenomenon is more likely in elevations near the 0°C isotherm, north-facing aspects, steep slopes (25–30°) and flat to slightly convex topographies. Indeed, they identify significant evidence of destabilisation (e.g., crevasses and scarps) at 46 active rock glaciers in the French Alps – 10% of all active rock glaciers in this region. Research considering the implications of future climate warming on rock glaciers is therefore much required, yet it remains in its infancy (Rangecroft et al., 2016). In one of the few studies to date, Rangecroft et al. (2016) modelled future MAAT projections at intact rock glacier sites in the Bolivian Andes. Assuming a conservative rock glacier activity threshold of +2°C (MAAT), the authors conclude that >98% of currently intact inventoried landforms will become relict by 2080. Similarly, within the Argentinian Andes >50% of currently active rock glaciers will terminate below the mean annual 0 °C isotherm by 2050 under RCP2.6 (i.e. best-case climate scenario) (Drewes et al., 2018). Under RCP8.5 (i.e. worst-case climate scenario) the majority will terminate below the mean annual 0 °C isotherm by 2070, e.g., 92.6% (~4120 of 4449 currently active rock glaciers) in the Central Andes sub-region (ibid.). While no allowances were made for a lagged response of rock glaciers to the modelled temperature shifts (see Rangecroft et al., 2016; Drewes et al., 2018), considering the above-described emerging observations, in a changing climate the hydrological significance of rock glaciers as long-term stores is questionable.

Importantly, however, establishing statistically significant correlations between meteorological variables (e.g., MAAT, snow cover [depth, duration, timing], summer temperature, positive degree days etc.) and rock glacier response mechanisms can prove challenging (Roer et al., 2005; Kellerer-Pirklbauer and Kaufmann, 2012; Hartl et al., 2016b; Scotti et al., 2017). As a consequence, it is highly likely that rock glacier kinematic behaviour and surface geometry are determined by a complex combination of geomorphic (e.g., rock glacier internal structure, underlying topography [slope angle, slope convexity]), environmental (e.g., short and long-term temperature change, snow cover – including depth, duration and timing, rainfall events) and paraglacial processes (e.g., landslide and/or rockfall driven debris overload of the rooting zone) (Krainer and He, 2006; Bodin et al., 2009, 2017; Delaloye et al., 2013; Schoeneich et al., 2015; Hartl et al., 2016b; Wirz et al., 2016; Scotti et al., 2017; Buchli et al., 2018; Eriksen et al., 2018). Here, it is important to stress that some rock glaciers yet to exhibit a climatically-forced response have been reported (Potter et al., 1998; Janke, 2005). Nevertheless, in the context of projected climatic warming, clearly, further research is required to critically quantify and assess rock glacier-climate relations and the associated implications for future water resources. To this end, research focused upon the response of rock glaciers to past environmental conditions could provide key information for validating projected responses to future climate warming; however, there is currently a paucity of such studies (Sorg et al., 2015).

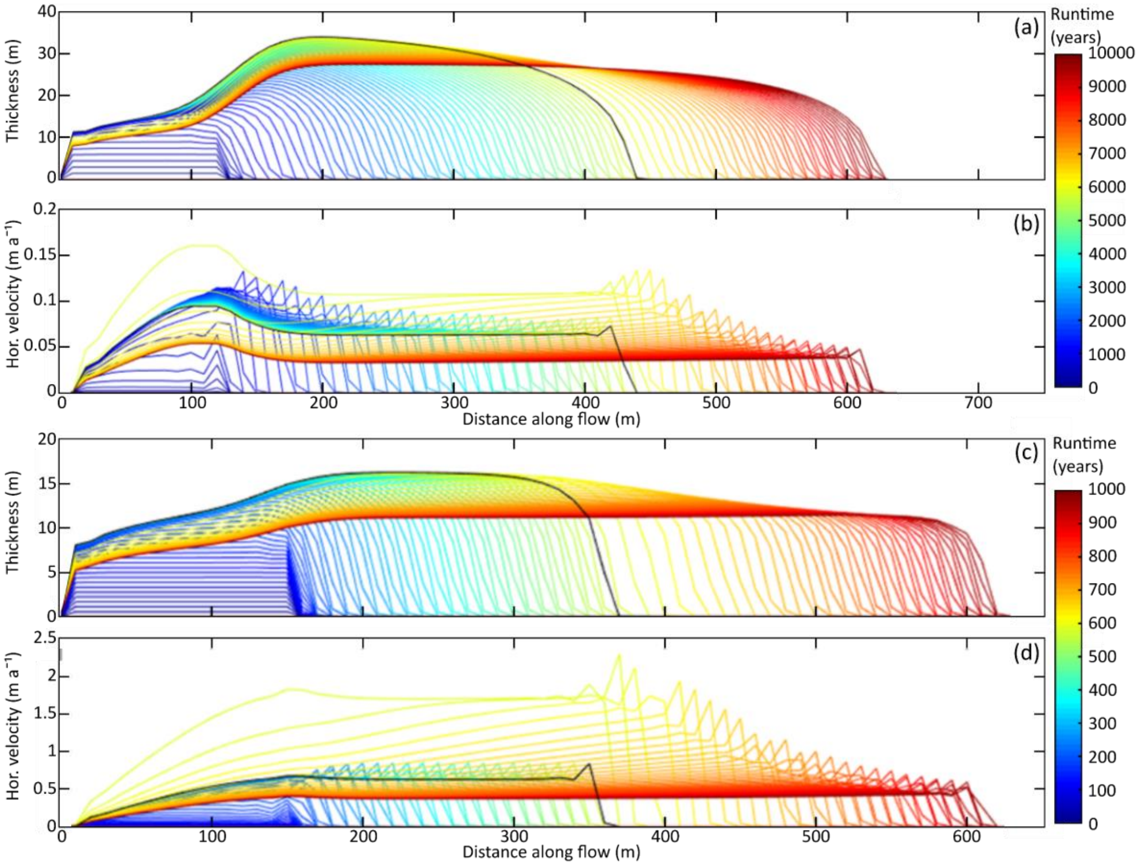

Fig. 5. Modelled evolution of absolute thickness and horizontal velocities along the central flow line of the Murtèl [a, b] and Huhh1 rock glaciers [c, d] introducing a 1°C temperature increase to the entire rock glacier body and 40% of the original material input following rock glacier build-up (Murtèl = 6000 years, Huhh1 = 600 years [black lines]). The black lines reflect the pre-perturbation state of the rock glaciers. A reference rock glacier temperature of -1.5°C was used, thus the 1°C temperature increase corresponds to a rate factor [referring to the material softness] increase by a factor of 1.7. The lines are plotted in 100 a steps [a, b] and 10 a steps [c, d]. Modified after Müller et al. (2016).

4. Rock glacier distribution and storage

A considerable number of rock glacier inventories have been compiled in various mountain ranges (see Jones et al., 2018a). However, as yet no global-scale (complete) inventory has been compiled, despite being described as the “most pressing need” in rock glacier research (Janke et al., 2013). It should be noted that significant recent research efforts have greatly elaborated inventory coverage in the succeeding years, for example in South America (Falaschi et al., 2014; Rangecroft et al., 2014; Falaschi et al., 2015; Falaschi et al., 2016; Azócar et al., 2017; Barcaza et al., 2017; Esper Angillieri, 2017; García et al., 2017; Janke et al., 2017; IANIGLA-CONICET, 2018; Selley et al., 2018), North America (Charbonneau and Smith, 2018; Munroe, 2018), Central Europe (Colucci et al., 2016; Kellerer-Pirklbauer et al., 2016; Roudnitska et al., 2016; Salvador-Franch et al., 2016; Triglav-Čekada et al., 2016; Winkler et al., 2016a; Onaca et al., 2017; Palma et al., 2017; Uxa and Mida, 2017; Fernandes et al., 2018; Popescu, 2018), Asia (incorporating Central Asia, South Asia [East], South Asia [West] and North Asia) (Bolch and Gorbunov, 2014; Schmid et al., 2015; Lytkin and Galanin, 2016; Galanin, 2017; Wang et al., 2017; Jones et al., 2018b; Ran and Liu, 2018; Blöthe et al., 2019), Antarctic and Subantarctic (Rudolph et al., 2018) and New Zealand (Sattler et al., 2016). Recently, Jones et al. (2018a) presented a near-global database containing >73,000 rock glaciers (intact = ~39,500, relict = ~33,500). The authors provide an approximate estimate of the water volume equivalent (WVEQ) stored within these rock glaciers as being 83.7 ± 16.7 Gt, equivalent to ~68–102 trillion litres (Fig. 6). Furthermore, excluding the Antarctic and Subantarctic and Greenland Periphery Randolph Glacier Inventory (RGI; Pfeffer et al., 2014) regions, along with RGI regions within which no systematic rock glacier inventories have been undertaken, the estimated ratio of rock glacier-to-glacier WVEQ is 1:456 globally, implying that glaciers store a volume of water 456 larger than rock glaciers currently, a ratio that will change under a warming climate due to the differential wasting rates of glaciers vs. rock glaciers, as previously discussed.

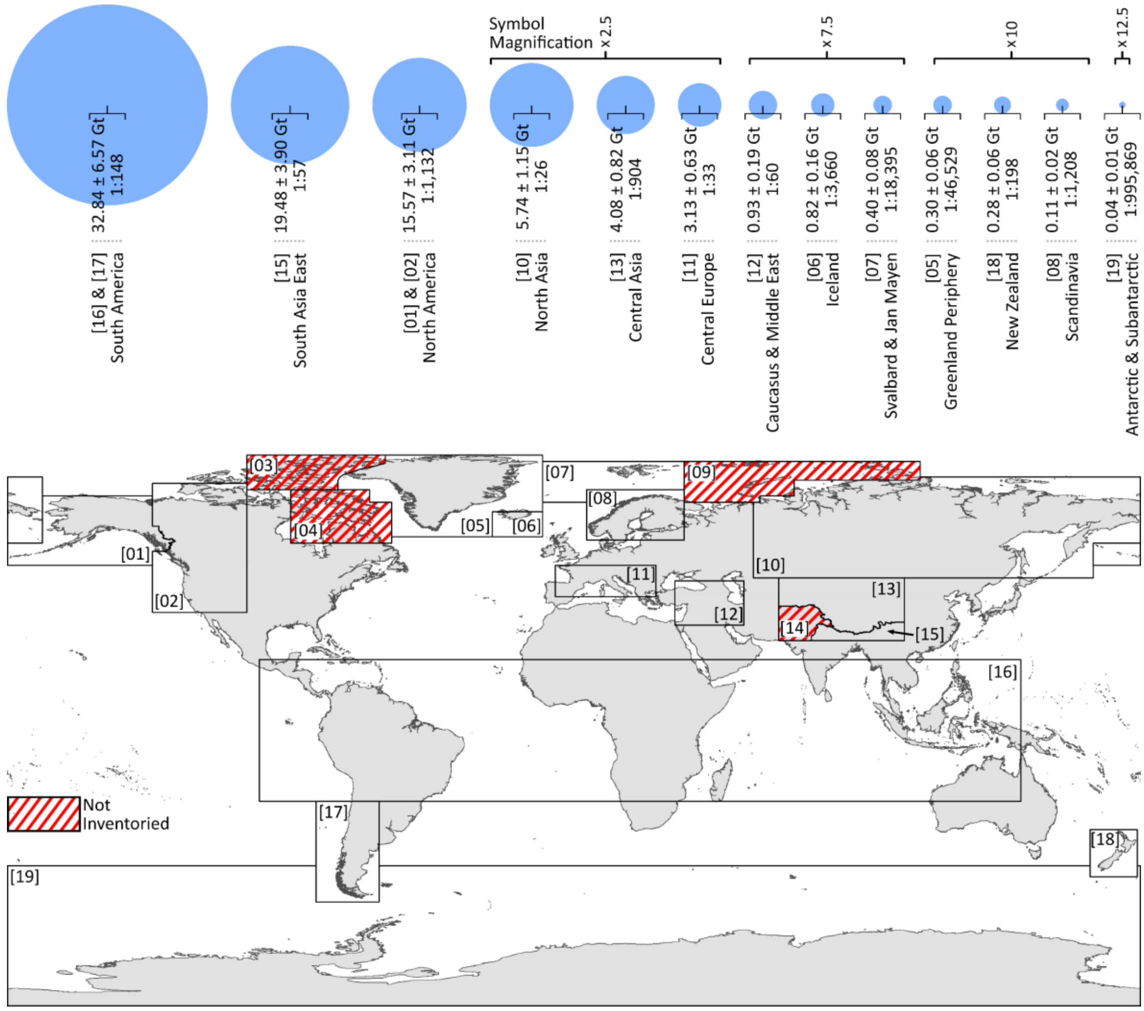

Fig. 6. Near-global rock glacier WVEQ (Gt) and ratios of rock glacier-to-glacier WVEQ. Rock glacier WVEQs (blue circles) are sized proportionately to the whole. Rock glacier WVEQs reflect 50 ± 10% ice content by volume. The data are organised into the first-order RGI regions, which are reflected in the accompanying world map. No systematic rock glacier inventory studies have been undertaken in RGI regions *03* (Arctic Canada North), *04* (Arctic Canada South), *09* (Russian Arctic), and *14* (South Asia West). Data are derived from Jones et al. (2018a).

Importantly, near-global- and RGI-regional-scale ratios (Fig. 6) suggest that rock glaciers form considerable water stores; however, arguably the abovementioned ratios mask the potential hydrological value of rock glaciers at national and regional level, particularly in semi-arid and arid zones where glacier presence is limited/absent. For example, rock glacier-to-glacier WVEQ ratios of 3:1 in parts of the Chilean Andes (29°–32° S) suggests that rock glaciers collectively contain more water than glaciers (Azócar and Brenning, 2010). Furthermore, Janke et al. (2017) conclude that rock glaciers constitute ~50% of surface water storage in the Aconcagua River Basin, further south in Chile. Elsewhere, studies in Bolivia estimate rock glacier-to-glacier WVEQ ratios to be 1:7 (Sajama region) (Rangecroft et al., 2015) and as high as 1:3 in the West region of Nepal (Jones et al., 2018b). This emphasises the importance of rock glaciers as non-negligible water stores. Indeed, the recently adopted National Glacier Law of Argentina[(2)] protects glaciers and rock glaciers as strategic water reserves, prohibiting detrimental human activities (e.g., mining and oil and gas activities) in their vicinity, recognising the potential hydrological value of such features. Nonetheless, although a small number of national-scale glacier inventories include rock glaciers, such as the Inventario Nacional de Glaciares of Argentina (Zalazar et al., 2017; IANIGLA-CONICET, 2018), they are omitted from global-scale glacier databases, e.g., the RGI (Pfeffer et al., 2014) or glacier outlines available from GLIMS (www.glims.org) – it is conceivable that in their absence, rock glaciers could be considered as hydrologically insignificant by the wider scientific community and decisionmakers. In addition, while rock glacier inventory density is high in certain areas (e.g., Central Europe [Jones et al., 2018a]) further inventories are required to better understand the hydrological significance of rock glaciers, particularly where future

(2) Law No. 26.639, "Minimum Standards Regime for Preservation of Glaciers and Periglacial Environment". Available to view online (in Spanish): http://servicios.infoleg.gob.ar/infolegInternet/anexos/170000-174999/174117/norma.htm.

climate warming will likely considerably impact freshwater resources in the long-term (e.g., Andes, Hindu Kush etc.). With this in mind, it is important to provide an overview of the techniques to assess both rock glacier distribution (Section 4.1) and subsurface characteristics (Section 4.2).

4.1. Approaches for assessing rock glacier distribution

Whereas debris-free glaciers can feasibly be mapped/monitored through the application of semi-automated and automated remote sensing classification techniques applied to optical satellite data (e.g., Bolch et al., 2010; Guo et al., 2015), the continuous debris-layer that characterises rock glaciers confounds such approaches. In explanation, rock glacier – and debris-covered glacier – surficial debris and debris from the surrounding slopes share a mutual origin, thus their spectral similarity "render[s] them mutually indistinguishable" (Shukla et al., 2010) using spectral properties alone. Accordingly, combined methodologies have been developed to identify debris-covered glaciers (Paul et al., 2016), for example using multispectral [optical and thermal] satellite data (e.g., Shukla et al., 2010); however, such approaches are generally unsuitable for mapping rock glaciers or heavily debris-covered glaciers (e.g., Brenning, 2009). Consequently, rock glacier inventory compilation by means of manual-recognition, -delineation and -classification (i.e. dynamic behaviour) using representative rock glacier features (Section 2.1; Fig. 1) (e.g., Scotti et al., 2013; Schmid et al., 2015) arguably remains the optimum approach. As such, rock glacier inventories are inherently subjective (see Scotti et al., 2013; Schmid et al., 2015; Jones et al., 2018b), influenced as they are by the expertise and field knowledge of the mapper. In particular, this is evident in the case of ongoing glacier-rock glacier interactions (cf. Monnier and Kinnard, 2015b; Section 2.2) where defining the divide between rock glaciers and debris-covered glaciers can prove challenging, especially where rock glaciers are not well-developed (i.e. lacking their characteristic surface features) (e.g., Mölg et al., 2018). These ongoing glacier-rock glacier interactions are commonly not included in either glacier, e.g., the RGI (Pfeffer et al., 2014) or GLIMS, or rock glacier inventories in spite of their potential future hydrological value and we argue their inclusion is of critical importance.

Of further influence on rock glacier inventory accuracy are the resolution and quality of both the terrain (i.e. digital elevation model and maps) and optical (i.e. aerial or satellite imagery) data used. The increased availability of spatial data with high repeat frequency in recent years has enabled existing rock glacier inventories to be updated, so the global picture is becoming more complete (e.g., Kellerer-Pirklbauer et al., 2012; Janke et al., 2017). Additionally, open-source and new types of data have provided enhanced opportunities for rock glacier mapping and monitoring, with: (i) fine spatial resolution optical data (e.g., QuickBird, WorldView-1 and 2, IKONOS) accessible freely through Google Earth enabling large-scale rock glacier inventories to be compiled (e.g., Rangecroft et al., 2014; Schmid et al., 2015; Jones et al., 2018b); (ii) finer than 1 m resolution LiDAR (light detection and ranging [i.e. airborne laser scanning]) data enabling heavily vegetated relict rock glaciers, which can significantly influence catchment hydrology (Winkler et al., 2016b) (see Section 5.3), to be mapped (e.g., Colucci et al., 2016); and (iii) InSAR (Interferometric Synthetic Aperture Radar) data (e.g., ESA Sentinel-1) enabling both rock glacier mapping and accurate classification of activity type through the investigation of surficial kinematics, such as feature displacement (Kenyi and Kaufmann, 2003; Strozzi et al., 2004; Lambiel et al., 2008; Echelard et al., 2013; Liu et al., 2013; Barboux et al., 2014; Wang et al., 2017; Imaizumi et al., 2018; Villarroel et al., 2018).

We argue that further research addressing the controls on rock glacier distribution and development (see Johnson et al., 2007; Forte et al., 2016; Kenner and Magnusson, 2017) could further exploit the abovementioned data to identify suitable "habitats" for rock glaciers, thereby encouraging more efficient inventory compilation in rock glacier data-deficient regions. Research efforts with respect to this, for instance, using statistical estimation techniques and generalised additive modelling with terrain/optical data (e.g., Brenning et al., 2007; Azócar and Brenning, 2010; Brenning and Azócar, 2010), have already been undertaken. Further improvements within this research area may enable semi-automated or automated identification and mapping of rock glaciers over larger spatial-scales in the future, although this would demand the use of new datasets, e.g., time-series of SAR interferometry data for distinguishing sedimentary areas experiencing ground deformation (rock glaciers) vs. static features. Critically, better knowledge of rock glacier distribution and more accurate classification of activity type and temporal dynamics will facilitate an informed assessment of future water supplies with respect to rock glaciers. Furthermore, inventories are time-static, and an ongoing concern should be regular monitoring of rock glaciers using up-to-date satellite data, to determine rates of change and wastage over large extents. With new satellite systems in orbit, such as the Sentinel-1 SAR constellation, we are entering a time where routine regular observations can be used to update inventories (e.g., Villarroel et al., 2018), and as Paul et al. (2016) explain this could "considerably improve over previous capabilities, thanks to increased spatial resolution and dynamic range, a wider swath width and more frequent coverage". Rock glacier scientists should also explore the capabilities offered by cloud-based image processing on Google Earth Engine, which could enhance the efficiency with which such large volumes of data can be processed in the future (Gorelick et al., 2017).

4.2. Approaches for assessing rock glacier subsurface characteristics

4.2.1. Internal structure

Information concerning the number, spatial distribution and morphometric characteristics of rock glaciers is useful; nevertheless, complementary subsurface data (i.e. internal structure: origin, thickness and proportional ice content, hydrological flowpaths) are required to better understand the hydrological role of rock glaciers. Knowledge of the subsurface properties of rock glaciers is derived predominantly from geophysical techniques such as ground-penetrating radar (GPR), electrical resistivity tomography (ERT) and seismic refraction tomography (for reviews see: Scott et al., 1990; Maurer and Huack, 2007; Kneisel et al., 2008; Hauck, 2013). Geophysical investigations suggest that rock glacier internal structure comprises four general layers: (i) a debris mantle (i.e. AL) with a thickness in the order of meters; (ii) an ice-rich (i.e. high ice content [vol.%]) frozen layer a few tens of metres thick; an ice-poor (i.e. low ice content) or ice-free sediments underlying the ice-rich layer; and (iv) the surface of the bedrock. For example, the Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) each comprise a 4–6 m thick AL that is underlain by ice-rich permafrost 20–30 m in thickness, then 10–15 m of ice-free sediments (Hausmann et al., 2012). The above-described subsurface composition has been confirmed through geophysical investigations at a number of other rock glaciers (e.g., Isaksen et al., 2000; Fabrot et al., 2005; Hausmann et al., 2007; Bodin et al., 2009). Furthermore, information from boreholes drilled through the well-studied Murtèl-Corvatsch and Muragl rock glaciers (Haeberli et al., 1998; Arenson et al., 2002) also support the general rock glacier internal structure as earlier described (Kääb, 2013). Importantly, rock glacier subsurface characteristics (e.g., AL thickness, multiple ice origins [i.e. freezing of sub- and supra-groundwater, seasonal snow accumulation, avalanching and buried glacial ice], volumetric ice content, permafrost table topography, rock debris abundance, etc.) within and between rock glaciers can be highly heterogeneous (Haeberli et al., 2006) (Fig. 7). Two cores drilled on the Lazaun rock glacier in the southern Ötztal Alps, Italy, further demonstrate the horizontal and vertical heterogeneity of rock glacier subsurface and ice content (Krainer et al., 2015; Fig. 8). This spatial heterogeneity is also reported at the Las Liebres rock glacier (Chilean Andes, Chile) where ice content markedly varies along a longitudinal GPR profile (22–83%) (Monnier and Kinnard, 2015a).

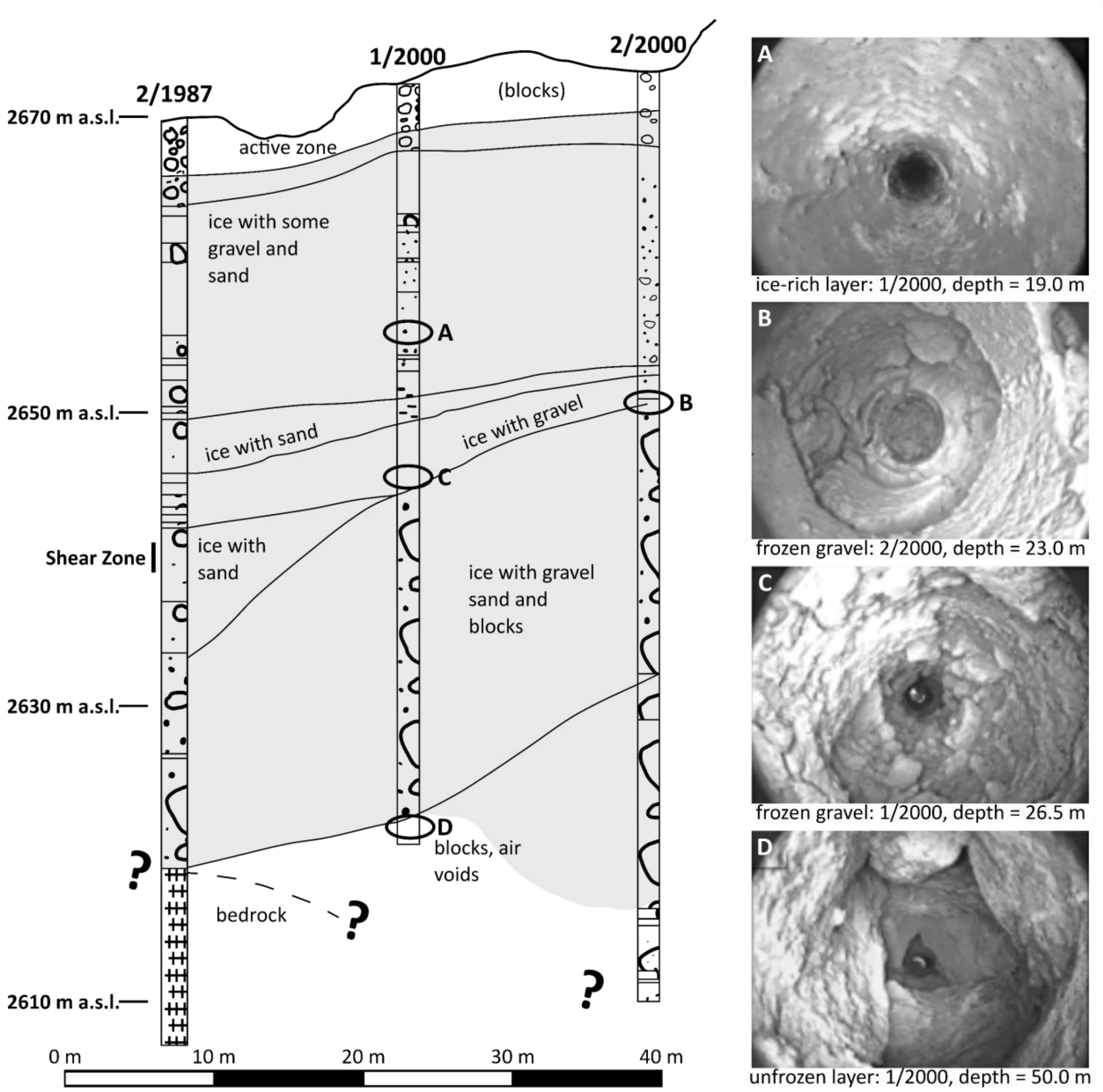

Fig. 7. Detailed stratigraphy of the Murtèl-Corvatsch rock glacier through three boreholes (BH 2/1987, BH 1/2000 and BH 2/2000) (Arenson et al., 2002). Photographs A-D from a borehole camera reflect the stratigraphy of the rock glacier at 19.0 m, 23.0 m, 26.5 m and 50.0 m depths. These subsurface investigations demonstrate the heterogeneity of rock glaciers, with zones of massive and interstitial ice present. Modified after Springman et al. (2012).

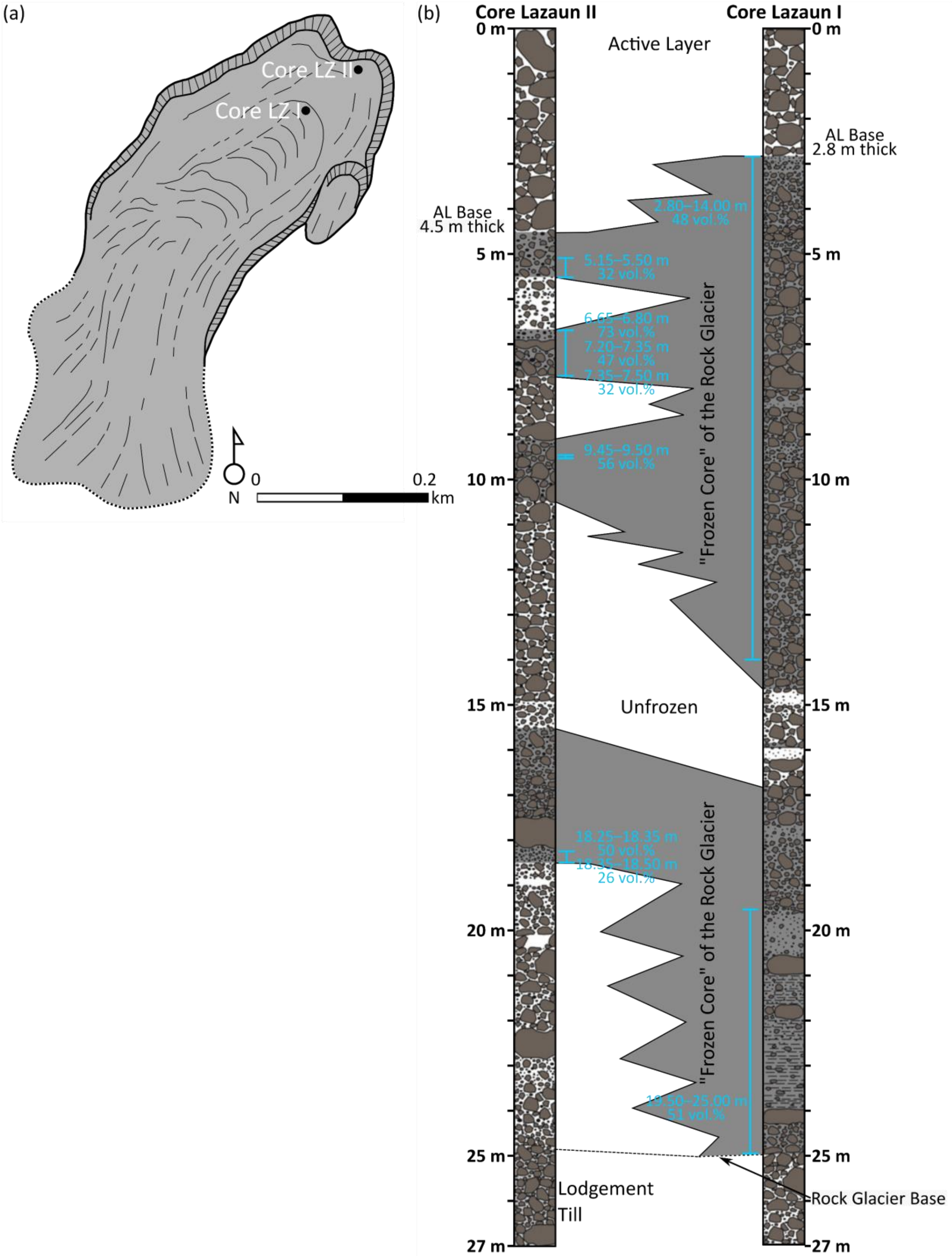

Fig. 8. (a) Map of the Lazaun rock glacier including the locations of core Lazaun I and II; and (b) the rock glacier internal structure from core Lazaun I and II. The average ice content of core Lazaun I is 43 vol.%, varying between 0–98 vol.% and core Lazaun II is 22 vol.%, varying between <2–73%. Examples of higher ice content within the cores are shown. Note the presence of intra-permafrost taliks (particularly in core Lazuan II), the formation of which has been attributed to advective and conductive heating by infiltrating water and circulating air (Luethi et al., 2017). Modified after Krainer et al. (2015).

While significant progress has been made regarding scientific knowledge of the interior characteristics of rock glaciers, such understanding is derived from a relatively small number of features due to the formidable logistical challenges of fieldwork in such environments (e.g., government restrictions on sampling and/or equipment use, field location accessibility, presence of large boulders and megaclasts [i.e. b-axis >4.1 m] at the surface [Fig. 4b]) that would require considerable expense and time to overcome, particularly drilling (Degenhardt Jr and Giardino, 2003; Janke et al., 2013). Indeed, very few rock glaciers have been drilled (see Table 3 in Haeberli et al., 2006). Therefore, although non- or minimally invasive geophysical techniques can rapidly provide 2-D subsurface data over extended survey areas, in contrast to 1-D information provided by drilling (Haeberli et al., 2010), geophysical investigations have rarely been validated by direct measurements (Degenhardt Jr and Giardino, 2003; Hauck and Kneisel, 2008). As a consequence, where detailed information on the density and composition of rock glaciers are unavailable and geophysical data quality is variable, significant uncertainties in the interpretation of geophysical data can occur due to ambiguities in relating subsurface data to material properties within the rock glacier (e.g., differentiating between rock and ice) (Hauck et al., 2011; Hauck, 2013).

In response, innovative, alternative methodologies have been developed; for example, at the Äußeres Hochebenkar rock glacier (Ötztal Alps, Austria), feature thickness was calculated using a simple creep model based on high-resolution surface displacement and slope data derived from multitemporal digital elevation models. Comparison of model results and GPR data proved helpful in fine-tuning the analysis of the latter (Hartl et al., 2016a). Also, where multitemporal high-resolution digital elevation models are available, rock glacier thickness and volume could be estimated with this method (Hartl et al., 2016a). As the modelling approach of Hartl et al. (2016a) accounts for individual rock glacier-specificities (i.e. rock glacier dynamics and local topography), estimated rock glacier thickness and volume will be more accurate than those generated using more general approaches, such as empirical power-law relations (Section 4.2.2).

Of further note, improved geophysical techniques will provide opportunities to improve understanding of rock glacier internal structure and ice content. For example, helicopter-mounted quasi-3-D GPR was recently successfully used to investigate the internal structure of Furggwanghorn rock glacier, Swiss Alps (Merz et al., 2015a; Merz et al., 2015b), overcoming some of the logistical challenges associated with detailed *in situ* geophysical surveys. Emmert and Kneisel (2017) found that quasi-3-D electrical resistivity tomography enables the mapping and monitoring of spatial variations within the rock glacier internal structure, with considerable potential to deliver new insights into surface and subsurface process-linkages. Additionally, the geophysically based 4-phase model (see: Hauck et al., 2011) combines electrical resistivity tomography and refraction seismic tomography measurements to obtain volumetric proportions and characterise the lateral and vertical distribution of the rock glacier constituents: air, water, ice, and rock. The model has already been successfully applied to rock glaciers for this purpose (e.g., Hauck et al., 2011; Schneider et al., 2013). Furthermore, Mewes et al. (2017) demonstrate the suitability of the 4-phase model for detecting interannual and seasonal phase change between liquid water and ice in rock glaciers; therefore, this model is a valuable tool for monitoring degradation of the internal ice body (Section 3). These new techniques will provide a platform to better understand the internal structure, dynamics and response of rock glaciers to future warming. In particular, more detailed geophysical investigations may enable volume and WVEQ estimation for glacier-rock glacier transitional forms (Section 2.2), for which simplified geomorphometric approaches (Section 4.2.2) are not suitable due to the internal complexity of such features (Bolch et al., 2019).

4.2.2. Volume and WVEQ

Since detailed subsurface information is available for only a limited number of rock glaciers, 2-D-area-related statistics have enabled first-order approximations of thickness and volume of unmeasured rock glaciers. In particular, *empirical thickness-area (H-S) relations* have been applied to predict rock glacier thicknesses and derive rock glacier volume (e.g., Brenning, 2005a; Azócar and Brenning, 2010; Bodin et al., 2010; Perucca and Esper Angillieri, 2011; Rangecroft et al., 2015; Janke et al., 2017; Jones et al., 2018a, 2018b). Empirical H-S relations can be expressed as $\bar{h} = c \cdot S^{\beta}$, where mean rock glacier thickness $\bar{h}$ (m) is calculated as a function of surface area S (km^2) and a scaling parameter c (50) and scaling exponent β (0.2) (Brenning, 2005a). Rock glacier volumes were determined by $V = \bar{h} \cdot S$. Rock glacier WVEQ was subsequently estimated through the multiplication of V and estimated ice content (% by vol.) and assuming an ice density conversion factor of 900 kg m^{-3} (Paterson, 1994).

To our knowledge, no study has evaluated empirical power-law relations (i.e. H-S and V-S [volume-scaling] scaling relations) for their suitability to approximate rock glacier thickness and volume. Empirical power-law relations have been evaluated in relation to glaciers (see Frey et al., 2014; Bahr et al., 2015), upon which they have more commonly been used to predict regional- and global-scale glacier thickness and volume (e.g., Chen and Ohmura, 1990; Bahr et al., 1997; Radić and Hock, 2010; Grinsted, 2013; Andreassen et al., 2015). Frey et al. (2014) demonstrate that considerable uncertainty is associated with the application of power-law relationships for this purpose. It is reasonable to assume that shortcomings experienced when applying these approaches to glaciers and rock glaciers are similar. Regarding V-A scaling relations (i.e. $V = c \cdot S^{\gamma}$ [where γ is β+*1*]) for glaciers, the scaling exponent γ is considered a constant (Bahr et al., 1997; Bahr et al., 2015) whereas the scaling parameter c should be considered as a variable determined by several parameters that vary between glaciers (e.g., basal topography, sliding parameters, ice-flow parameters) (Bahr et al., 2015). Further, several researchers have suggested different, region-specific values for both c and γ from regression of the available data (see Grinsted, 2013). Brenning's (2005a) empirical power-law relation was developed from morphometric field measurements at 19 rock glaciers in the Andes of Santiago, Chile (Bodin et al., 2010). As such, this approach cannot account for regional specificities of rock glaciers around the world (e.g., dominant ice origin, local climatic parameters, local topography, etc.) (Jones et al., 2018a) that could reasonably be expected to influence the value of scaling parameter c, as described above. To date, a constant scaling parameter c and scaling exponent β have thus been used in rock glacier studies applying Brenning's (2005a) empirical power-law relation (e.g., Brenning, 2005a; Azócar and Brenning, 2010; Bodin et al., 2010; Perucca and Esper Angillieri, 2011; Rangecroft et al., 2015; Janke et al., 2017; Jones et al., 2018a, 2018b). Therefore, use of such methods with respect to rock glaciers requires careful and critical evaluation. To improve the effectiveness of empirical power-law relations for rock glaciers requires that (i) the physics (i.e. dynamics) of rock glaciers are better understood, (ii) the sample size used to constrain the scaling parameter c and choose the value for β needs to be increased, and (iii) the scaling parameter c is localised.

Previous studies predicting rock glacier WVEQ have assumed a 'typical' volumetric rock glacier ice content of 50% (Brenning, 2005b; Azócar and Brenning, 2010; Perucca and Esper Angillieri, 2011) – WVEQ values for 40–60% vol. (i.e. lower [40%], mean [50%] and upper [60%] estimates) are sometimes provided to account for uncertainty (Brenning, 2005a; Bodin et al., 2010; Rangecroft et al., 2015; Jones et al., 2018a; Jones et al., 2018b) – consistent with *in situ* data derived from different climatic regions worldwide (e.g., Elconin and LaChapelle, 1997: >50%; Arenson et al., 2002: 40–70%; Croce and Milana, 2002: ~55%; Hausmann et al., 2007: 45-60%; Hausmann et al., 2012: 40–60%). Importantly, studies that have used Brenning's (2005a) empirical power-law relation – excluding Janke et al. (2017) – have considered intact rock glaciers (i.e. active and inactive rock glaciers treated collectively). Yet, Arenson and Jakob (2010) suggest that the application of the abovementioned statistical model should better differentiate between the volumetric ice content of active and inactive rock glaciers. Indeed, a classification system for debris-covered glaciers and rock glaciers divides the latter into three subclasses: (i) "Class 4: Proper" (i.e. active), ice content = 25–45%; (ii) "Class 5: Transitional" (i.e. inactive), ice content = 10–25%; and (iii) "Class 6: Glacier of rock" (i.e. relict), ice content = <10% (Janke et al., 2015). As a consequence, large uncertainties will be introduced to rock glacier WVEQ predictions by the typically lower volumetric ice content of inactive rock glaciers (Brenning, 2010). In addition, existing rock glacier WVEQ estimations have not considered volumetric air content, reported to be up to 25% in intact rock glaciers (Arenson and Springman, 2005), that would further reduce predicted WVEQ (Arenson and Jakob, 2010). Nonetheless, existing rock glacier WVEQ estimations provide a much-needed first approximation that should stimulate further research and gain the attention of policymakers.

5. Rock glacier water discharge

5.1. Characteristics of rock glacier discharge

To date, only very few studies have investigated the hydrological aspects of rock glacier water discharge, in spite of recent research reporting that rock glaciers constitute non-negligible long-term water stores (Section 4). Besides the above-stated formidable logistical challenges of rock glacier-related fieldwork (Section 4.2.1), this is because water discharge measurements are challenging or virtually impossible to conduct for rock glaciers (i) with multiple, often inaccessible springs (Krainer et al., 2012), (ii) with no spring(s), i.e. the water drains within the debris (Krainer and Mostler, 2002), (iii) that grade into downslope landforms, and (iv) that terminate in lakes or ponds (Colombo et al., 2018c). Based on the few available measurements, the discharge from springs of intact rock glaciers is estimated to range from <1 to >1000 L s^{-1} during the melt season (Table 2).

Table 2. Discharge from intact rock glaciers during the melt season.

Rock Glacier Name	Location	Discharge (L s^{-1})	Reference
Gruben	Swiss Alps, Switzerland	2–50	(Haeberli, 1985)
Hilda	Rocky Mts., Alberta, Canada	90–270*	(Gardner and Bajewsky, 1987)
Dos Lenguas	Central Andes, Argentina	5–8	(Schrott, 1991, 1996)
East Slims River	St. Elias Mts., Yukon, Canada	0.7–3.7	(Harris et al., 1994)
Morenas Coloradas	Central Andes, Argentina	230–1000	(Trombotto et al., 1997)
Reichenkar	Stubai Alps, Austria	20–375	(Krainer and Mostler, 2002)
Gößnitz	Hohe Tauern Mts., Austria	5–310	(Krainer and Mostler, 2002)
Innere Ölgrube	Ötztal Alps, Austria	30–1000	(Berger et al., 2004)
Kaiserberg	Ötztal Alps, Austria	25–600	(Krainer et al., 2007)
Reichenkar	Stubai Alps, Austria	20–450	(Krainer et al., 2007)
Mt. Tukuhnikivatz	La Sal Mts., Utah, USA	0.1–25.2	(Geiger et al., 2014)
Lazaun	Southern Ötztal Alps, Italy	9–140	(Krainer et al., 2015)
Äußeres Hochebenkar	Ötztal Alps, Austria	10–300	(Nickus et al., 2015)

* The Hilda rock glacier has been classified as an inactive rock glacier (Luckman and Crockett, 1978). Furthermore, (Harris et al., 1994) note that the rock glacier spring "is actually a groundwater spring mantled by the rock glacier", and thus the results may not reflect only rock glacier discharge.

Intact rock glacier discharge patterns are characterised by strong seasonal and diurnal variability, primarily determined by local weather conditions, the thermal conditions within the AL, and the physical mechanisms that control meltwater flow through the rock glacier (Krainer and Mostler, 2002; Berger et al., 2004; Krainer et al., 2007; Krainer et al., 2015). The water released from intact rock glaciers is derived from (i) melting of the winter snowpack, (ii) melting of glacier ice, (iii) melting of rock glacier ice, (iv) rainfall, particularly during summer thunderstorms with heavy rainfall, and (v) groundwater (Krainer and Mostler, 2002). The contribution to intact rock glacier discharge of the abovementioned water sources changes considerably during the melt season. Typically, discharge rates are highest during the spring/early summer snowmelt and gradually decline through summer and autumn to low or zero flow in the winter months. In addition, rock glacier discharge fluctuates strongly in response to rainfall events and periods of colder weather with snowfall (Johnson, 1981; Blumstengel and Harris, 1988; Krainer and Mostler, 2002; Berger et al., 2004; Krainer et al., 2007) (Fig. 9). Further, intense melting of the winter snowpack during periods of warm weather produce marked diurnal runoff cycles, with low discharge at noon and peak discharge towards late evening (Krainer and Mostler, 2002). In this respect, generally, rock glacier discharge patterns mimic those of glaciers, although at considerably lower magnitude (Krainer and Mostler, 2002; Geiger et al., 2014). Additionally, various authors suggest that rock glacier discharge fluctuates less than glaciers (Potter, 1972; Corte, 1976, 1987; Gardner and Bajewsky, 1987), at least on diurnal timescales (Haeberli, 1985; Pourrier et al., 2014); however, few have demonstrated this empirically.

Isotopic analyses of rock glacier springs, alongside discharge and electrical conductivity sampling (EC) data, support the above-described seasonal evolution of intact rock glacier discharge composition (Krainer and Mostler, 2002; Berger et al., 2004; Williams et al., 2006; Krainer et al., 2007). For example, Krainer et al. (2007) report that rock glacier discharge in the Stubai and Ötztal Alps, Austria, exhibits: (i) intermediate $\delta^{18}O$ values at the beginning of the melt season, reflecting the mixed origin of runoff from re-frozen meltwater from the preceding autumn (high $\delta^{18}O$) and snowmelt (low $\delta^{18}O$); (ii) significantly reduced $\delta^{18}O$ and EC values following the onset of spring discharge, with runoff predominantly derived from snowmelt; and (iii) gradually increasing $\delta^{18}O$ and EC values during the melt season, which reflect the continued depletion of the winter snowpack and increased icemelt (i.e. melting of the frozen rock glacier core) and groundwater contributions. Intermittent sharp peaks in rock glacier discharge, $\delta^{18}O$ values and concomitant depressions of EC suggest that outflows temporarily derive predominantly from summer rainfall events (which have higher $\delta^{18}O$ values and are EC-depleted) (Krainer et al., 2007; Fig. 9).

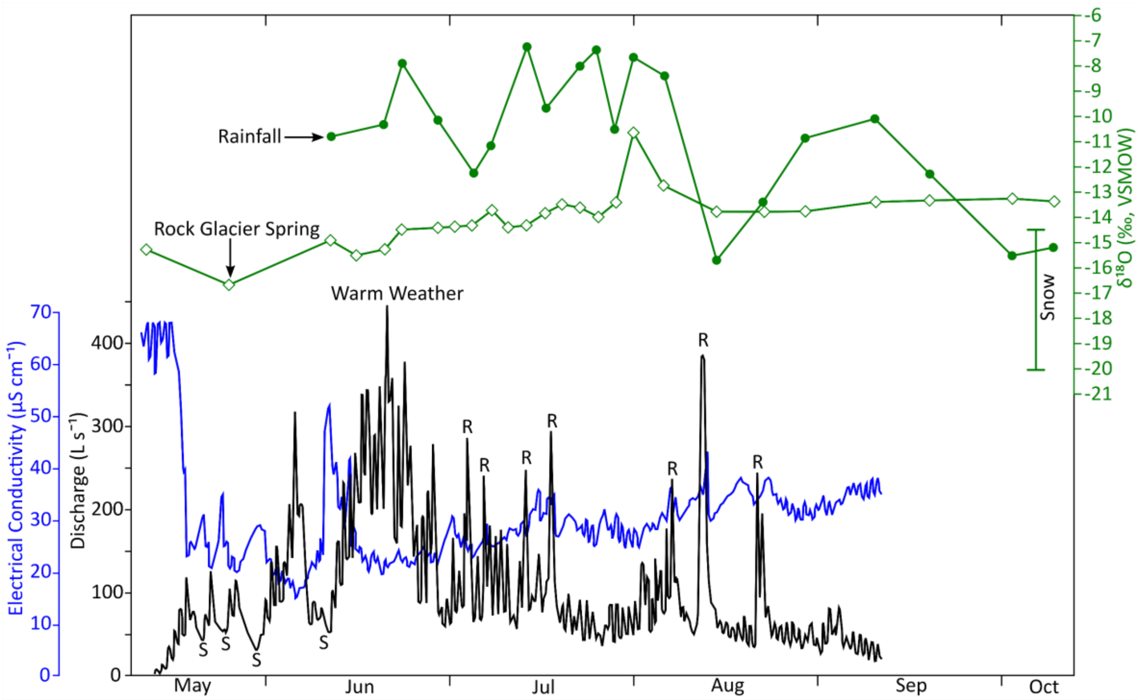

Fig. 9. Hydrograph of the meltwater stream at the Reichenkar rock glacier and EC between mid-May and mid-September 2002. Major snowfall (S) and rainfall (R) events are indicated. Oxygen isotope composition ($\delta^{18}O_{water}$) of the rock glacier spring and rain precipitation is also depicted for the period from mid-May to mid-October 2002. The snow profile was sampled in April 2002. Of note, $\delta^{18}O$ values of the frozen rock glacier core (not depicted) are similar to those of the rock glacier spring. Modified after Krainer et al. (2007).

Of note, previous studies have primarily investigated the temporal evolution of $\delta^{18}O$ in conjunction with discharge and EC data to ascertain the origins of rock glacier outflows. Yet hitherto very few attempts have been made to determine the proportional contribution to rock glacier discharge of different sources. Williams et al. (2006) analysed the outflow components of the Green Lake 5 rock glacier (Colorado Front Range, USA) through geochemical and stable isotopic analyses in combination with end-member mixing analysis: 30% was snowmelt, 32% was soil water, and 38% was baseflow – the latter includes icemelt. Notably, studies have not successfully isolated the contribution of icemelt to rock glacier discharge (Krainer et al., 2007); however, seasonal discharge, $\delta^{18}O$ and EC data, as prior discussed, suggest water released from rock glaciers principally derives from snowmelt, glacial meltwater and intermittent rainfall events, with negligible or non-measurable contributions derived from icemelt (Croce and Milana, 2002; Krainer and Mostler, 2002; Krainer et al., 2007). Minimal icemelt contributions are predominantly due to the insulative effects of the AL, which prevents substantial melt rates (Section 3). For instance, Krainer et al. (2015) estimate that melting of the frozen rock glacier core contributed ~0.6 L s^{-1} or ~2.3% of the total annual mean discharge of ~26 L s^{-1} during the melt season at the Lazaun rock glacier. At the Helen Creek rock glacier (Banff National Park, Alberta, Canada) – an inactive feature – minimal icemelt contributions (3–5% [July-August]) support these findings (Harrington et al., 2018). Elsewhere, using radioisotope analysis, Cecil et al. (1998) compared tritium concentrations in rock glacier outflows (9.2–13.2 TU [Tritium Units]) to those in an ice core at the same location (-1.3–0.2 TU). They conclude that frozen rock glacier core formation pre-dates the peak of above-ground nuclear weapons testing (1950s/1960s), whereas rock glacier outflows primarily derive from modern precipitation (i.e. minor contributions from icemelt).

Notably, rock glacier-catchment hydrology interactions remain poorly understood and opinions regarding the hydrological contributions of rock glaciers diverge. Indeed, a number of studies have suggested that rock glacier hydrological contributions to downstream runoff are significant; however, the majority of these conclusions are based upon non-quantitative data (for summary see: Duguay et al., 2015). It is important to note that investigations focused upon rock glacier hydrology generally consider present as opposed to future rock glacier hydrological contributions. Therefore, thus far the hydrological significance of rock glaciers has been defined according to a restricted timescale. Critically, while rock glaciers form long-term water stores and thus may not constitute a readily available water resource (Duguay et al., 2015; Rangecroft et al., 2015), at decadal and longer timescales, under climate warming, degradation of the frozen rock glacier core may represent an increasing hydrological contribution to streamflow (Thies et al., 2013; Geiger et al., 2014).

5.2. Characterisation of rock glacier hydrological flowpaths

Importantly, as well as rock glacier hydrological contributions, rock glacier-catchment hydrology interactions should be considered with respect to discharge timing. In addition to the seasonal availability of different water sources (Section 5.1), rock glacier discharge timing is determined by spatially- and temporally-variable, convoluted subsurface flowpaths (Burger et al., 1999). Based upon the following information, a model of the hydrological flowpaths within rock glaciers of periglacial and glacial origin was constructed (Fig. 10).

Conceptual models of rock glacier hydrology suggest that subsurface water movement occurs along two flowpath types: *supra-permafrost flow* and *sub-permafrost flow* atop and below an impermeable frozen rock glacier core, respectively (Giardino et al., 1992). This is consistent with the conclusions of Krainer and Mostler (2002) who identified two storage reservoirs, the "quickflow reservoir" (herein *quickflow*) and "baseflow reservoir" (herein *baseflow*), which correspond to supra-permafrost flow and sub-permafrost flow, respectively. Rock glacier hydrographs, dye tracer tests and EC values demonstrate that quickflow and baseflow have significantly different characteristics of water storage and release (Krainer and Mostler, 2002). These characteristics are likely determined by the AL thickness (i.e. depth of the 0 °C isotherm), hydraulic connectivity, sedimentological characteristics, and the degree of rock glacier activity (i.e. volumetric ice content [% by vol.]) (Tenthorey, 1992; Harris et al., 1994; Krainer and Mostler, 2002; Williams et al., 2006; Buchli et al., 2013).

Dye tracer test results reported in Tenthorey (1992) and Krainer and Mostler (2002) indicate flow velocities of 54–327 m h^{-1}, demonstrating that the coarse-blocky openwork structure of the AL promotes quickflow. Elsewhere, the rapid temporal evolution of rock glacier discharge in conjunction with $\delta^{18}O$ and EC values suggests that waters derived from high-intensity weather events (i.e. intense snowmelt or summer rainfall events) are generally transmitted through active rock glaciers as quickflow with a lag time of a few hours (Krainer et al., 2007; Fig. 9). These results also show that quickflow occurs predominantly as channelised flow along a network of conduits eroded into the frozen rock glacier core (Krainer and Mostler, 2002). Occasionally, quickflow is visible and/or audible in the AL of intact rock glaciers (Tenthorey, 1992; Krainer and Mostler, 2002; Berger et al., 2004; Rogger et al., 2017).

Baseflow contributions are likely to form a relatively small proportion of water discharge and are characterised by high EC values, indicating that baseflow predominantly derives from slow diffuse groundwater flow transiting through unfrozen, fine-grained material at the base of the rock glacier (e.g., Krainer and Mostler, 2002). Investigations of the internal structure of active rock glaciers confirm the presence of ice-free, fine-grained sediments at the base of rock glaciers (Section 4.2.1), supporting the presence of the baseflow reservoir. Water tracer tests indicate that baseflow exhibits highly variable residence times, ranging from several days to several months (e.g., Tenthorey, 1992; Harris et al., 1994). Following depletion of the snow cover, rock glacier hydrographs and EC data demonstrate that baseflow contributions increase (e.g., Krainer and Mostler, 2002).

A further subsurface flowpath in rock glaciers with low ice content, *intra-flow* (i.e. slow internal flow), was identified through dye-tracing experiments (Tenthorey, 1992, 1994). Intra-flow also includes water transiting through active rock glaciers by means of unfrozen drainage networks, i.e. *intra-permafrost flow* (Tenthorey, 1992, 1994; Krainer and Mostler, 2002). Intra-permafrost flow has been reported at depth in the frontal portions of active rock glaciers (e.g., Arenson et al., 2010). In explanation, Ikeda et al. (2008) suggested that networks of air voids and fractures develop within the frozen rock glacier core as a result of fast deformation rates, based upon data from the Büz North rock glacier (Swiss Alps), and thus increased intra-permafrost flow throughout the landform. This has significant implications for rock glacier creep velocities and stability, including via the reduction of effective stress by infiltrated water (Krainer and Mostler, 2006; Perruchoud and Delaloye, 2007; Ikeda et al., 2008); however, these implications are not discussed here. Typically, intra-flow is released from the rock glacier as baseflow.

Importantly, geophysical methodologies, such as the 4-phase model (Section 4.2.1), provide opportunities to estimate the liquid water content within the frozen rock glacier core and to identify preferential subsurface flowpaths (Mewes et al., 2017, and references therein). Limitations and required improvements within the 4-phase model are detailed in Hauck et al. (2011) and Mewes et al. (2017).

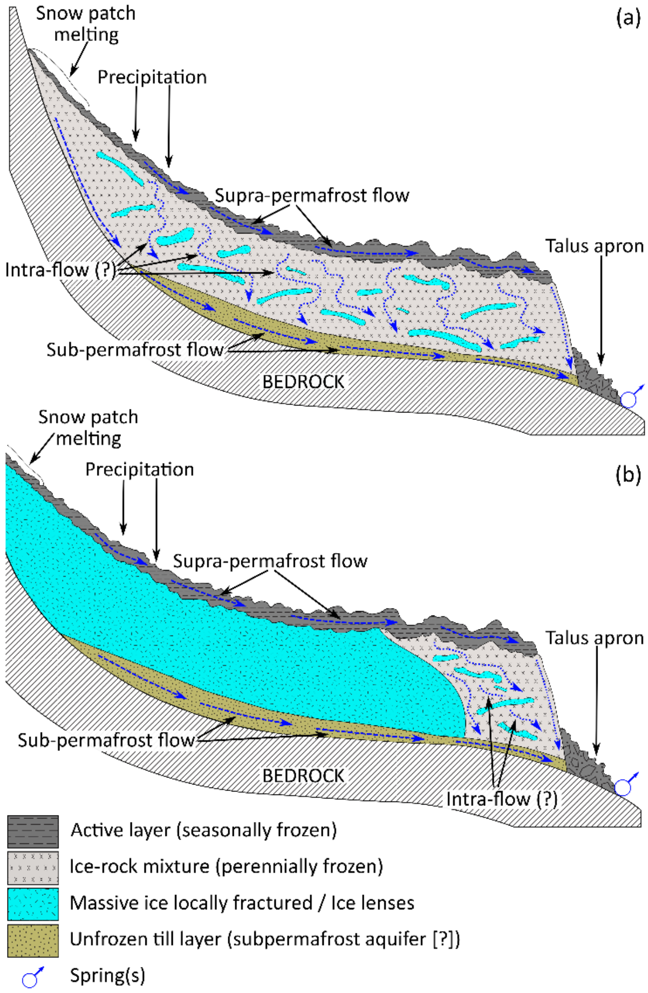

Fig. 10. A simplified hypothetical model of hydrological flowpaths through an active rock glacier of: (a) periglacial origin; and (b) glacial origin. N.B. hydrological flowpath terminology was maintained for [a] and [b] for consistency (i.e. supra-*permafrost*, intra-*permafrost*, and sub-*permafrost* flow), regardless of the dominant ice origin. Arrows depict the flowpath direction.

5.3. Rock glacier-catchment hydrology interactions

Very few systematic studies of catchment-scale geomorphic drivers of streamflow regimes (i.e. timing, magnitude and duration of discharge) have conducted comparative assessments of the hydrological response between alpine catchments. Physical catchment parameters, including slope, elevation range, drainage area, and bedrock geology, have previously been used assess inter- and intra-catchment variations in the hydrological response. Contrastingly, the hydrological influence of discrete debris accumulations (DDAs) and/or ice-debris landforms (I-DLs), e.g., talus slopes, protalus ramparts, protalus lobes, and rock glaciers, are largely neglected (Weekes et al., 2015). N.B. ground ice exists within I-DLs. Yet, recent research demonstrates that DDAs and I-DLs can modulate the hydrologic response (e.g., Clow et al., 2003; Geiger et al., 2014; Weekes et al., 2015; Rogger et al., 2017).

In the La Sal Mountains, Utah, a comparative assessment of an [active] rock glaciated vs. non-rock glaciated catchment indicates that the presence of active rock glaciers had a pronounced influence upon catchment hydrology (Geiger et al., 2014). Hydrographs from the rock glaciated (i) and non-rock glaciated catchments (ii) are distinctly different. (i) In this catchment, flood peaks are delayed following the onset of precipitation, flood peaks are higher, and the proportion of precipitation leaving the catchment as stormflow is high. (ii) Contrastingly, in this catchment, flood peaks occur much more quickly and are short in duration, and the proportion of precipitation leaving the catchment as stormflow is significantly lower than in the rock glaciated catchment (see Table 2 in Geiger et al., 2014). This indicates that in non-rock glaciated catchments, significant losses of precipitation to deep groundwater storage may occur. Importantly, rock glacier hydrographs have shown that rock glacier stormflow constitutes a significant proportion of total catchment runoff (15–30%). It appears that the proportion of rock glacier stormflow to catchment stormflow is determined by precipitation intensity rather than precipitation volume. For example, 37.6 mm of precipitation (1.21 mm h^{-1}) and 7.2 mm of precipitation (2.40 mm h^{-1}) derived from two different storms resulted in a 15% and 30% contribution to total catchment runoff, respectively. The above-described observations indicate that active rock glaciers act as impervious surfaces following high-intensity weather events, with the net effect of increasing runoff generation within rock glaciated catchments (Geiger et al., 2014). In the Krummgampen catchment, western Ötztal Alps, Austria, model simulations indicate that complete disappearance of permafrost will reduce flood peaks by ~17%, supporting the above-described findings (Rogger et al., 2017).

Notably, the characteristics of rock glacier water storage and release (i.e. storage behaviour) differ considerably between active, inactive, and relict features. Indeed, lessening of the degree of activity through degradation of the frozen rock glacier core may potentially increase feature porosity, and thus increase the storage capacity. In turn, this will cause changes in the rock glacier discharge pattern, and consequently influence runoff generation in alpine catchments (Rogger et al., 2017). In response, several scientific studies have considered rock glacier-catchment hydrology interactions in relation to relict features (e.g., Wagner et al., 2016; Winkler et al., 2016b; Rogger et al., 2017). Globally, relict rock glaciers are numerous (Section 4) and under future climate warming intact rock glaciers will transition towards relict activity status, and thus from quickflow to baseflow dominated landforms. In explanation, the coarse-blocky open-work structure of rock glaciers promotes rapid infiltration and transmission of water inputs to the groundwater system – i.e. relict rock glaciers constitute unconfined aquifers (Geiger et al., 2014). For example, research in the Niedere Tauern Range (Eastern Alps, Austria) has shown that subsequent to precipitation events, relict rock glaciers rapidly (within hours) contribute ~20% precipitation volume to discharge; the remaining ~80% is delayed considerably with a mean residence time of ~7 months. This large storage component facilitates large baseflow rates long after precipitation events (Winkler et al., 2016b). As a consequence, relict rock glacier water stores can maintain streamflow during summer baseflow periods (e.g., Wagner et al., 2016). In addition, a large proportion of the terrain >2000 m a.s.l. drains through rock glaciers (e.g., Seckauer Tauern Range = 51% [Winkler et al., 2016a]); therefore, it is reasonable to assume that relict rock glaciers constitute significant water stores at intermediate-term timescales. Notably, to date studies assessing rock glacier WVEQ (Section 4.2.2) have not included relict rock glacier water stores; however, including these stores would introduce large uncertainties into WVEQ estimations, likely due to the difficulty of estimating such transient stores. Nevertheless, it is clear that this rock glacier type strongly influences both the water storage capabilities and discharge behaviour of alpine catchments.

Investigations of rock glacier-catchment hydrology interactions that consider large glacier-rock glacier composite features are sparse. At the Tapado catchment (Coquimbo region, Chile) – an assemblage of cascading cryospheric landforms (debris-free glacier, debris-covered glacier, rock glacier and moraine complexes) – Pourrier et al. (2014) found that the storage capacity and transmissive function of rock glaciers is considerably different to debris-covered glaciers. Pourrier et al. (2014) present a conceptual model that synthesises the hypothesised hydrological functioning of this glacier-rock glacier composite feature (Fig. 11). Analysis of the flow dynamics shows rapid and concentrated or slow and diffuse hydrological transfers for the debris-covered glacier and rock glacier, respectively. In this study, the debris-covered glacier forms a weakly capacitive but highly transmissive medium, whereas the rock glacier forms a highly capacitive but weakly transmissive medium. The hydrological data suggest that rock glaciers exhibit: (i) a strong buffering effect on the daily-to-monthly variability of transferring glacier meltwater to downstream areas; and (ii) a high storage capacity that partially delays glacier meltwater transfer to downstream areas (Pourrier et al., 2014). Therefore, catchment hydrology will be significantly influenced by glacier-rock glacier interactions, particularly where debris-covered glaciers are *currently developing* into rock glaciers. As a consequence of the transition from glacial to paraglacial process regimes, glacier-to-rock glacier transition in high mountain systems is increasingly likely (Section 2.2); therefore, it is important to better understand the catchment hydrology implications of glacier-rock glacier interactions.

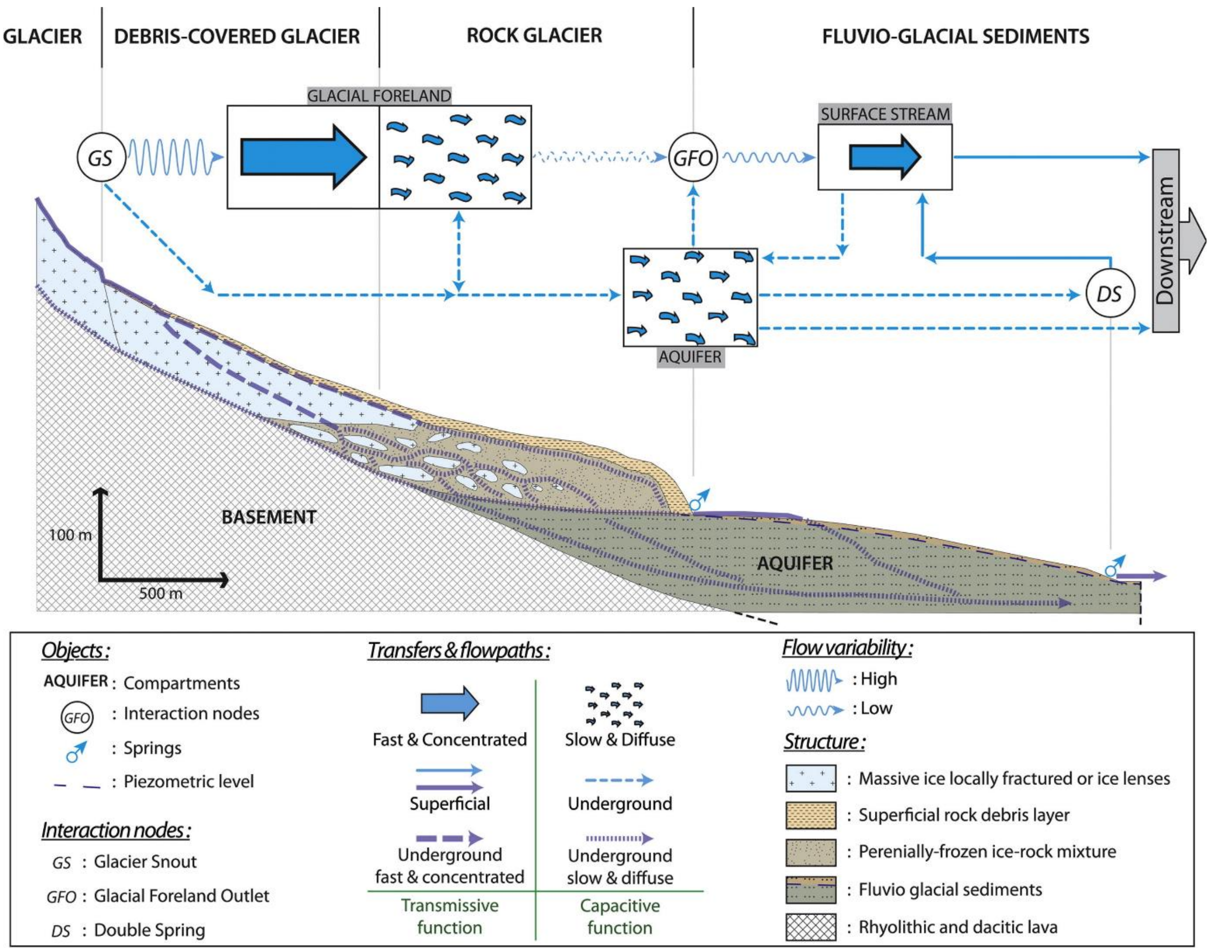

Fig. 11. Schematic transect through the Tapado catchment synthesising the hypothesised hydrological interactions between the catchment components (i.e. debris-free glacier, debris-covered glacier, rock glacier, and fluvioglacial sediments). Figure after Pourrier et al. (2014).

6. Rock glacier water hydrochemistry

Rock glacier water hydrochemistry is the focus of very few scientific investigations (see Table 1 in Colombo et al., 2018b). It is known that rock glaciers lose ice volume at slower rates than glaciers (Section 3), therefore the former potentially affect water hydrochemistry over longer timescales (Fegel et al., 2016). Indeed, work has shown that rock glacier thaw modifies the inorganic chemistry of both water bodies located downstream (Thies et al., 2007; Baron et al., 2009; Ilyashuk et al., 2014; Colombo et al., 2018a; Ilyashuk et al., 2018) and streams (Williams et al., 2006; Thies et al., 2013; Nickus et al., 2015; Fegel et al., 2016; Munroe, 2018). As a consequence, the water quality characteristics of rock glacier outflows should be a major focus of research, given their potential as potable water resources (Burger et al., 1999).

Previously, rock glacier outflow has been described as *clear* (i.e. predominantly sediment free), containing comparatively lower *suspended sediment concentrations* (SSC) and higher *total dissolved solids* (TDS) relative to glacier-fed outflow (Gardner and Bajewsky, 1987). In addition, *total load* (i.e. SSC + TDS [excluding bedload transport]) within the latter are at least one order of magnitude greater than that within rock glacier outflow (Gardner and Bajewsky, 1987). It is important to note that these conclusions are based on a small sample size, with just a small number of studies evidencing this. For example, SSC measurements from the Hilda rock glacier (Canadian Rocky Mountains, Canada) were generally low, ranging between 1–3 mg L^{-1} and reaching 20 mg L^{-1} only in response to precipitation events. As expected, increased rock glacier-derived discharge causes increases in SSC; however, a threshold value of ~150 L s^{-1} was reported after which SSC declines (Gardner and Bajewsky, 1987). SSC measurements reported for the Boundary glacier, situated ~1 km north of the Hilda rock glacier, ranged between 70–4000 mg L^{-1} ($\bar{X}$ = 600–800 mg L^{-1}) during the same precipitation event (Gardner and Bajewsky, 1987), illustrating the potential filtering effect of rock glaciers on fine-grained sediment throughput. SSC measurements from the Reichenkar rock glacier (western Stubai Alps, Austria) reflect clear outflow associated with discharges <100 L s^{-1}, but SSC of 1000 mg L^{-1} recorded at peak discharges of >300 L s^{-1} (Krainer and Mostler, 2002); SSC-discharge relationships are therefore unclear. TDS measurements of rock glacier outflow are generally low, although they have been shown to be significantly greater than those of glacier and snowmelt derived outflow. For instance, TDS values of 60–75 mg L^{-1} and 30–40 mg L^{-1} were reported for Hilda rock glacier and Boundary glacier outflow, respectively (Gardner and Bajewsky, 1987).

Rock glaciers characteristically have a higher debris fraction versus glaciers. Consequently, it is hypothesised that significant mineral surface area-ice contact promotes chemical weathering and leads to solute-enrichment of water contained within rock glaciers (Ilyashuk et al., 2014, 2018). This hypothesis is consistent with the results from Giardino et al. (1992) who reported that rock glacier outputs in the San Juan Mountains (Colorado, USA) had significantly higher TDS than rock glacier inputs. Rock glacier input pH levels (6.4–6.9) and output pH levels (7.3–8.4), further illustrate the solute-concentrating effect of rock glaciers (Ilyashuk et al., 2014). Giardino et al. (1992) recorded similar pH values for rock glacier inputs (6.4–7.0) and outputs (7.2–8.5) at three features in the Blanca Massif area of the Sangre de Cristo Mountain Range, Colorado, USA. Given that rock glacier thaw resulting from climate change could drive the export of enriched-solute fluxes, the analysis of EC, major ions (e.g., Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-) and trace elements (e.g., Ni, Mn, Al, Hg, Pb) in rock glacier outflow has received increasing attention (for review see: Colombo et al., 2018b).

In the American West (i.e. Cascade Mountains, Rocky Mountains, Sierra Nevada), Fegel et al. (2016) report that rock glacier outflow samples exhibit higher pH and EC values and are also enriched in *weathering products* (i.e. SiO_2, Ca^{2+}, K^+, Mg^{2+} and Sr^{2+}) relative to glaciers. Similarly, Crespo et al. (2017) report higher EC values for rock glacier-derived waters ($\bar{x}$ = 1201 μS cm^{-1}) compared to waters from debris-free glaciers ($\bar{x}$ = 32 μS cm^{-1}), snow-dominated streams ($\bar{x}$ = 159 μS cm^{-1}) and debris-covered glaciers ($\bar{x}$ = 805 μS cm^{-1}) in the Upper Mendoza River basin (Argentinian Andes). In addition, clear differences in the $\delta^{18}O$ signatures of glacier- (debris-free and debris-covered) vs. rock glacier-derived waters are reported; depleted values (i.e. lower amount of heavy isotopes) and enriched values (i.e. higher abundance of heavy isotopes) are found in glacier- and rock glacier-derived waters, respectively (ibid.). To date, research directly comparing rock glacier- and glacier-derived meltwaters through hydrochemical and stable isotope analysis are few in number; most consider the hydrochemistry of rock glacier outflows over various timescales or relative to surface waters uninfluenced by rock glaciers (not explicitly of glacial origin). Long-term (1985–2005) increases in EC (by ~19-fold), Ca^{2+} (by ~13-fold), SO_4^{2-} (by ~26-fold) and Mg^{2+} (by ~68-fold) have been reported for the Rasass See alpine lake located beneath an active rock glacier in the Central Eastern Alps, Italy (Thies et al., 2007; Fig. 12). Increased enriched-solute fluxes related to rock glacier thaw are reflected in the strong seasonal variations found in outflow hydrochemistry. For instance, strong seasonal increases in SO_4^{2-} (by ~175-fold), Mg^{2+} (by ~30-fold), Ca^{2+} (by ~20-fold) and Na^+ (by ~4-fold) were recorded for Green Lake 5 rock glacier (Colorado Front Range, Rocky Mountains, USA) outflows in late summer/autumn compared with other surface waters during mid-summer (Williams et al., 2006). Such findings have been attributed to enhanced rock glacier thaw due to climate warming (Thies et al., 2007; Thies et al., 2013).

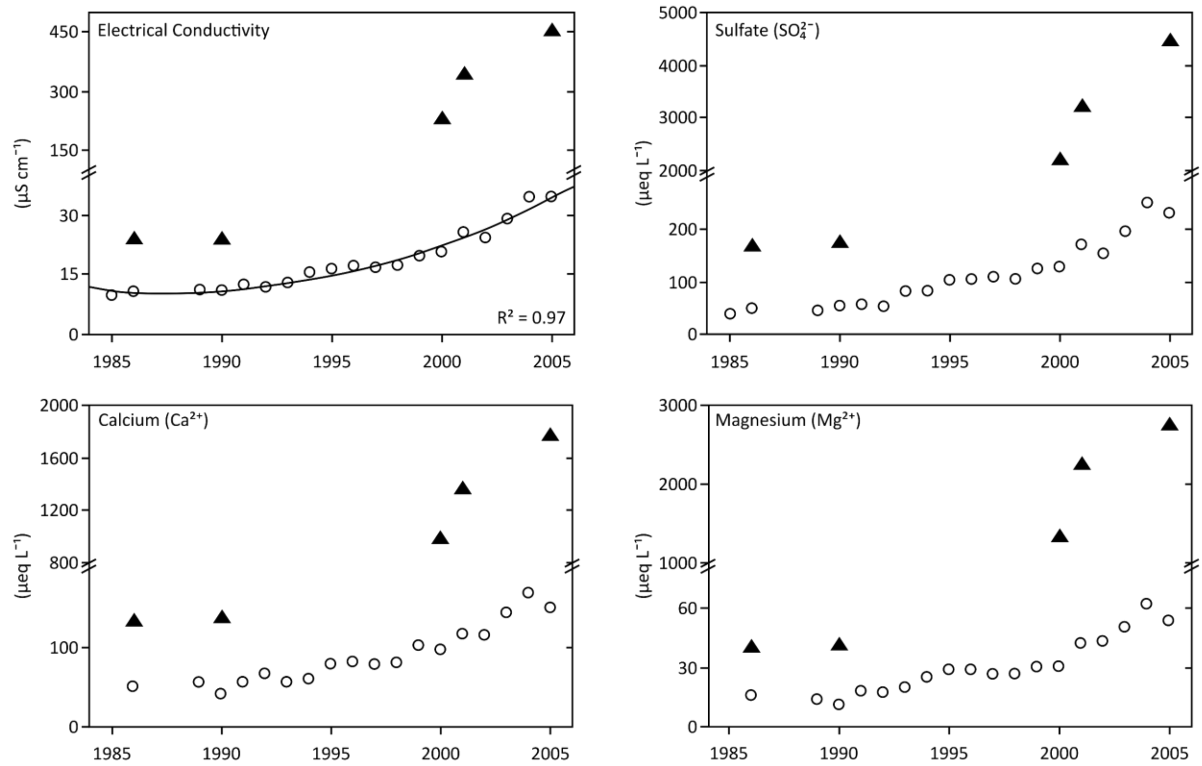

Fig. 12. Long-term EC, sulfate (SO_4^{2-}), Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations in Rasass See (black triangles) and Schwarzsee ob Sölden (open circles) alpine lakes (1985–2005). Values for Rasass See and Schwarzsee ob Sölden represent mean values of four to seven discrete samples along the lake vertical profile taken during holomixis (i.e. compete mixing of the lake). Variability among single values is <5%. Diagonal lines on the y-axis depict scale breaks. Modified after Thies et al. (2007).

Elevated concentrations of trace elements in high-altitude alpine lakes, also attributed to the influence of rock glacier thaw (Thies et al., 2007), have been reported. For instance, natural *acid rock drainage* (ARD) can arise in mineralised catchments with sulfide-bearing lithologies following rock glacier thaw, as the exposure of sulfide-rich rocks to air and oxygenated water results in increased oxidation of sulfide minerals (Ilyashuk et al., 2014). ARD typically produces acid-sulfate waters enriched in metals; for example, high concentrations of Mn, Ni and Al in excess of EU maximum permissible levels in drinking water were recorded at Rasass See. Contrastingly, negligible concentrations were reported for the adjacent water body without a rock glacier in its catchment (Ilyashuk et al., 2014). In mineralised catchments with sulfide-bearing lithologies, under future climate warming, it is reasonable to expect enhanced ARD in response to increased AL thickness which permits atmospheric oxygen to penetrate to greater depths (Colombo et al., 2018b). Additionally, high-altitude mining operations may adversely affect rock glacier water quality as mining tailings – a source of ARD (Bellisario et al., 2013) – are piled onto rock glacier surfaces (Brenning, 2008; Bellisario et al., 2013). Of note, the origin(s) of high concentrations of trace elements in rock glacier ice often remains the subject of considerable uncertainty (Colombo et al., 2018b) and requires further study. For instance, high heavy metal concentrations (Ni, Zn, Co, Cu, Fe and Mn) were determined in ice-cores drilled at Lazaun rock glacier, yet lithological analyses indicate the origin of these heavy metals is not the rocks of the catchment area of the rock glacier (Krainer, 2014; Krainer et al., 2015).

As described above, localised releases of enriched-solute fluxes following rock glacier thaw can alter significantly the inorganic chemistry of water surfaces downstream. Further, increased export of enriched-solute fluxes can be expected under future climate warming. Therefore, an improved understanding of the meteorological drivers (i.e. air temperature, snowmelt and rainfall) responsible for the export of solute-enriched waters from rock glaciers is important for (i) determining causality for the hydrochemical response of water surfaces downstream and (ii) anticipating, monitoring and planning for future changes in downstream hydrochemistry (Colombo et al., 2018a). Three hypotheses are identified (Colombo et al., 2018b): (i) warmer air temperatures enhance rock glacier thaw, releasing solute-enriched waters (e.g., Krainer and Mostler, 2002; Berger et al., 2004; Williams et al., 2006; Krainer et al., 2007; Thies et al., 2013; Nickus et al., 2015; Colombo et al., 2018a); (ii) long-lasting snow cover delays rock glacier thaw thus soluble materials remain sequestered in rock glacier ice, while snowmelt also dilutes solute-enriched waters

(Williams et al., 2006). Similarly, rainfall percolation through rock glaciers lowers solute concentrations in outflows (e.g., Krainer and Mostler, 2002; Berger et al., 2004; Krainer et al., 2007; Nickus et al., 2015); and (iii) rainwater percolating through rock glaciers flushes solute-enriched waters, particularly following snow cover depletion (e.g., Colombo et al., 2018a), in contrast to the effects described in hypothesis (ii). This lack of agreement likely stems from the limited availability of studies focused on meteorological variables, hydrologic processes and chemical characteristics of water surfaces downstream (Colombo et al., 2018a). Further, existing studies have predominantly been undertaken in the European Alps or North American mountain ranges (Colombo et al., 2018b). As such, it is evident that further scientific investigation is required, particularly an extension of research evidencing the suitability of water surfaces downstream of rock glaciers for use as safe, potable water sources to other regions worldwide.

7. Conclusions

In this contribution, we synthesise the available literature and present the first comprehensive evaluation of the hydrological role of rock glaciers over a range of spatial and temporal scales, considering globally-distributed published studies. Of note, rock glacier-related research has advanced considerably post-1970s, yet important gaps remain regarding the scientific knowledge and understanding of rock glacier hydrology. A general lack of consensus concerning the present and future hydrological significance of rock glaciers pervades the literature.

Importantly, water storage within rock glaciers occurs over a range of timescales; yet, to date we identify that investigations focused upon rock glacier hydrological significance generally consider present as opposed to potential future rock glacier icemelt contributions – rock glacier hydrological significance has been defined according to a restricted timescale. A near-global first-order approximation of intact rock glacier WVEQ (water volume equivalent) concludes that intact rock glaciers potentially constitute hydrologically valuable long-term stores (see Section 4). Given that rock glaciers are climatically more resilient than glaciers (see Section 3), we hypothesise that the relative importance of rock glacier hydrological contributions will increase as climate warming proceeds through the twenty-first century, particularly in semi-arid and arid regions. Furthermore, with continued climate-driven deglaciation and thus a transition from glacial- to paraglacial-dominated process regimes, glacier-to-rock glacier transition is likely to become increasingly common (see Section 2). This may potentially enhance the resilience of the mountain cryosphere to future climate warming.

Thus far, rock glacier-related research has primarily defined the hydrological significance of rock glaciers according to the ice content/WVEQ and/or the proportional contribution to rock glacier discharge of icemelt. However, for the first time, we have synthesised published work to consider rock glacier "hydrological significance" as encompassing: (i) rock glacier-catchment hydrology interactions (i.e. total discharge volume, variability, and timing); and (ii) rock glacier effects upon the physical characteristics (i.e. hydrochemistry, temperature, etc.) of water inputs. Regarding (i), hydrographs from [active] rock glaciated and non-rock glaciated catchments have been reported to be distinctly different, and relict rock glaciers – regularly overlooked in rock glacier hydrology research – can also strongly influence alpine catchment hydrology (see Section 5). In regard to (ii), hydrochemical analysis of rock glacier outflows indicates that rock glaciers may adversely affect the inorganic chemistry of water bodies located downstream and streams (see Section 6).

In undertaking this detailed synthesis, we have identified candidate areas for future rock glacier hydrology research, which are currently absent or require further development in the literature. In general, there exists a relative paucity of quantitative data that continues to restrict scientific assessment of rock glacier hydrological significance, presumably owing to the formidable logistical challenges of rock glacier-related fieldwork globally (see Section 4). Importantly, we identify that quantitative data are needed from a range of locations and timescales. In particular, we would suggest that there is an urgent requirement for studies to deliver data describing the long-term characteristics of rock glaciers, capturing the full diversity of morphometry and environmental settings of these features. This will require efforts within the research community to tackle sites that are less easily accessible since much of the existing research has been conducted to date on the most accessible sites (e.g., within the European Alps), which may provide a limited viewpoint. We call for further research into the following:

- *Rock glacier distribution:* Considerable research efforts have significantly elaborated rock glacier inventory coverage; analysis of inventory data, including rock glacier number, distribution, and morphometric characteristics, forms the first step in understanding their hydrological role. However, rock glacier inventories are absent in many climatically vulnerable regions (e.g., Andes, Hindu Kush, etc.), and relatively few studies share accessible open-access databases (Jones et al., 2018a). Therefore, to enable improved inventory coverage we suggest: (i) existing inventories are made accessible; (ii) habitat suitability models are further developed, thereby encouraging more efficient inventory compilation in rock glacier data-deficient regions; (iii) use of open-access platforms, such as Google Earth; (iv) updated remote sensing data (see Section 4.1) is used to re-evaluate existing inventories. The recently established IPA Action Group (2018–2020), the primary aims of which are "to sustain the first steps toward the organization and the management of a network dedicated to rock glacier mapping (inventorying) and monitoring all around the world and the definition of the necessary standards" support these suggestions (Delaloye et al., 2018).
- *Rock glacier evolution:* It is hypothesised that glacier-to-rock glacier transitions are critically important in the context of future water resources management. Further work is needed to elucidate the drivers behind which glaciers will fully transition into rock glaciers and those which will simply downwaste. This requires a future research focus on *currently developing* features. Furthermore, *currently developing* features are commonly not included in either glacier or rock glacier inventories. To assess their potential future hydrological value efforts to inventory glacier-rock glacier interactions (e.g., Bolch et al., 2019) need to be undertaken.
- *Rock glacier ice content/WVEQ:* Currently, an empirical power-law relationship ($\bar{h} = c \cdot S^{\beta}$) is predominantly used to evaluate rock glacier ice content and thus WVEQ, but there are few empirical studies against which to test the rigour of this relationship (see Section 4). We call for new experiments that: (i) enable the physics (i.e. dynamics) of rock glaciers to be better understood, (ii) increase the sample size used to constrain the scaling parameter c and choose the value for β, and (iii) localise the scaling parameter c. We also call for ground-truthing data that will deliver the evidence-based science to test and review the suitability of the current empirical power-law relationship. Furthermore, an approach to estimate the ice content/WVEQ of glacier-rock glacier interactions, for which simple empirical power-law relationships are likely inappropriate (Bolch et al., 2019), needs to be developed.
- *Rock glacier storage and release:* There is some understanding about the short-term volume, variability, and timing of rock glacier outflows, derived from studies at a few, largely intact sites. As climate change progresses, rock glaciers will evolve, and there is a need for data describing how the transition towards relict activity status will impact discharge. This requires a focus on *space for time substitution* experiments across the intact-to-relict transition. In addition, geophysical methodologies, such as the 4-phase model (see Section 4), provide opportunities to better understand the internal structure of rock glaciers, and thus boost knowledge about subsurface hydrological processes (i.e. preferential subsurface flowpaths). We recognise that delivering empirical data describing rock glacier internal structure is difficult but encourage rock glacier scientists to engage with new methodological/technological approaches to sample rock glacier internal structure.
- *Rock glacier hydrochemistry:* Based upon a limited number of studies, there is evidence that intact rock glaciers can adversely change the inorganic chemistry of water bodies and streams, downstream of outflows. Further scientific investigation of this is required, to extend research evidencing the suitability of water originating from rock glaciers for use as safe, potable water resources. Importantly, future studies should assess waters originating from relict rock glaciers, as hydrological storage capacity and residence time is greater than that of intact features (Colombo et al., 2018b). We note that to include *hydrochemical sampling* in the experimental design of future rock glacier studies would advance this research field.
- *Rock glacier climatic resilience:* A number of studies conclude that complex internal thermal regimes are generated within the coarse-blocky openwork structure of the AL, amplifying the insulation effect of the debris mantle. However, in a changing climate intact rock glaciers could experience drastic change. Indeed, emerging observations of increased rock glacier surface velocities potentially in response to recent climate warming has been reported (see Section 3). In spite of this, research considering the effects of future climate warming on rock glaciers is in its infancy. Improved modelling of the thermal regime (i.e. heat transport) to study the future evolution of rock glaciers under different climate change scenarios (e.g., Pruessner et al., 2018) is critically needed. Further, this will better inform the long-term hydrological role of rock glaciers.

Notes

Author contribution. SH proposed the concept for the study as part of the PhD supervision of DBJ. The manuscript was based on a decade-old draft written by SH and WBW. DBJ researched and wrote the manuscript. SH and KA co-edited the manuscript with DBJ and WBW commented on the final version.

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