INVESTIGATING HOLOCENE MOUNTAIN GLACIATIONS: A PLEA FOR THE SUPREMACY OF GLACIAL GEOMORPHOLOGY WHEN RECONSTRUCTING GLACIER CHRONOLOGIES (supported by an example from the Southern Alps/New Zealand)

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With 10 figures and 1 table
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Summary: Investigating Holocene glacier chronologies constitutes a valuable approach within palaeoclimatic research. Recent progress of numerical dating techniques, in particular terrestrial cosmogenic nuclide dating (TCND), has given it new momentum. Highly increased precision and improved methodological procedures of data calibration seem, however, to have gradually pushed previous rigorous geomorphological analysis of the investigated glacier forelands aside. By using a well-known key site in the Southern Alps/New Zealand it is demonstrated that even alleged benchmark studies are not immune to geomorphological uncertainties. Considerable potential misinterpretations are alerting and reinforce the demand for an unaltered 'supremacy' of geomorphology in this context. Especially with global compilations aiming at wider palaeoclimatic conclusions critical re-assessment of glacier chronologies may occasionally seem necessary.

Zusammenfassung: Die Erforschung holozäner Gletscherchronologien stellt einen wichtigen Ansatz innerhalb der Paläoklimaforschung dar. Jüngste Fortschritte hinsichtlich numerischer Datierungstechniken, insbesondere bei der terrestrischen kosmogenen Nuklid-Datierung, haben diesem Forschungszweig neue Impulse gegeben. Die erheblich gesteigerte Präzision deren Ergebnisse in Verbindung mit verbesserten Kalibrierungsverfahren haben jedoch die vormals gründliche geomorphologische Analyse der untersuchten Gletschervorfelder in den Hintergrund gedrängt. Am Beispiel einer bekannten Schlüssellokalität in den Southern Alps/Neuseeland wird aufgezeigt, dass selbst vermeintliche Grundsatzarbeiten nicht immun gegenüber geomorphologischen Unsicherheiten sind. Erhebliche potentielle Fehlinterpretationen sind alarmierend und bestätigen eine notwendigerweise unveränderte Vormachtstellung der Geomorphologie in diesem Zusammenhang. Besonders auf paläoklimatische Schlussfolgerungen abzielende, weltweite Zusammenstellungen dürften eine kritische Überprüfung von Gletscherchronologien fallweise erforderlich machen.

Keywords: Quaternary geology, glacial geomorphology, mountain glaciations, Holocene glacier chronology, numerical dating techniques, New Zealand

1 Introduction

1.1 Mountain glaciers – the general context

Mountain glaciers constitute valuable (palaeo) climatic archives. Concurrently, they are impressive indicators of present climate change and deserve high attention of scientists, policy makers, and the public (WGMS 2008; Alean 2010; Lozán et al. 2015). Future changes within the high mountain cryosphere will exert significant impact beyond the geo-ecosystems upon, for example, natural risk assessment and sustainable economic development in mountain regions (Huber et al. 2005; Beniston et al. 2018). This explains the current effort of monitoring mountain glaciers and developing reliable predictions of their future behaviour (Bamber and Payne 2004; Haeberli et al. 2007; Slaymaker and Kelly 2007; Zemp et al. 2009; Barry and Gan 2011; Kargel et al. 2014; Tedesco 2015). Leading motivation for the investigation of Holocene glacier fluctuations is to utilise glaciers as valuable archives for climate variability in the past. The ability of mountain glaciers to record short- as well as mid- and long-term climatic variability is seen as an advantage over other climate proxies. Their response to different influencing factors (e.g. seasonal air temperatures, seasonal precipitation, and solar insolation) may reveal valuable insights about their climatic drivers, indispensable knowledge for any subsequent assessment of both present changes and predictions of future developments with their geo-ecological impact (Winkler et al. 2010). Consequently, every reconstruction of Holocene glacier chronologies has the hidden or pronounced aim

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to yield reliable palaeoclimatic information enabling the investigation of causes, mechanisms, and patterns of climate variability on local, regional, hemispheric, or global scales. Not least the importance of this goal is mirrored in recent IPCC reports (IPCC 2001, 2007, 2014) where palaeoclimatic data based on Holocene glacier chronologies subsequently gained broader room and higher attention (cf. Caseldine et al. 2010).

At global scale, mountain ranges typically experience multiple layers of natural diversity creating considerable challenges for the study of their former or current glaciations. Spatial differences of the climatic framework interacting with specific glaciological characteristics and regimes need to be emphasised alongside influencing dynamic geomorphological process systems in this context. A number of conceptual reviews (e.g. Owen et al. 2009; Slaymaker and Embleton-Hamann 2018) recently highlighted the resulting necessity of integrated approaches for the study of mountain glaciations. This is not a trivial task and involves more potential uncertainties caused by the abovementioned diversity than, for comparison, the investigation of polar ice-cores or large palaeo-ice sheet. For any reliable interpretation of Holocene glacier archives on basis of indispensable correlations that provide insight in global climate dynamics with their hemispheric and global interconnections it is, therefore, an essential prerequisite to ensure a satisfactory spatial diversity combined with credible and representative regional data series. Despite remarkable recent progress even the latest global compilations of Holocene glacier chronologies (Wanner et al. 2008; Solomina et al. 2015, 2016) reveal that only for very few study areas/mountain ranges all necessary requirements for an unproblematic utilisation for their palaeoclimatic potential as demanded by Kirkbride and Winkler (2012) can be rated as fulfilled. This situation is highly unsatisfactory because the existing uncertainties caused by various reasons still prevent a sustainable utilisation of mountain glacier's potential as palaeoclimatic archives. Due to better availability of accurate and high-resolution data, better comparability to the modern climate development, and the chance to achieve better spatial diversity by covering more mountain regions most literature on Holocene glacier fluctuations focuses on neoglacial events and in particular the so-called 'Little Ice Age'. Additionally, there is a clear bias towards the Northern Hemisphere with few exceptions of well-studied regions in the Southern Hemisphere, for example the central Southern Alps of New Zealand (Fig. 1):

1.2 Investigating Holocene glacier chronologies

For any assessment of Holocene glacier chronologies beyond (late) 'Little Ice Age' advances that can 'absolutely' be dated thanks to historical documents or early scientific reports and maps,

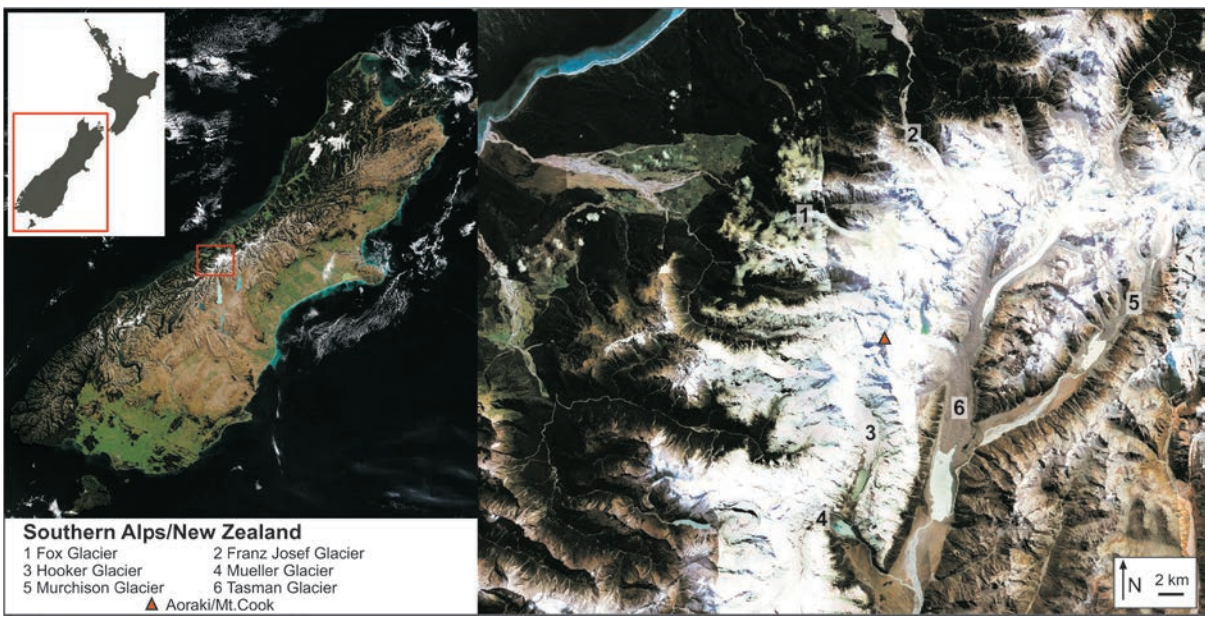

Fig. 1: Satellite imagery of the central Southern Alps/New Zealand with major glaciers and the summit of Aoraki/Mt.Cook indicated (modified after (left, April 2010) NASA Earth Observatory and (right, February 2013) GoogleEarth)

provision of information about selected approaches to achieve age constraints or about applied dating techniques is crucial. Early work on Holocene glacier forelands often focused on relative-age dating techniques before radiocarbon dating subsequently allowed obtaining numerical ages for moraines and other glacial landforms. Most of these studies contained detailed geomorphological mapping of the glacier forelands investigated. Considerable attention was drawn to the formation of moraines and related geomorphological analysis of the sites (cf. Grove 1979, 2004). A good example is the internationally undervalued work of Röthlisberger (1986). It does not only provide one of the first global compilations of glacier chronologies (mainly) based on radiocarbon dating but also includes remarkable conceptual models of lateral moraine formation (cf. Röthlisberger and Schneebeli 1979, Winkler and Hagedorn 1999). Highly detailed site descriptions allow reliable interpretation of his reported numerical ages. Given that their geomorphological and glacier chronological context is reported in a comprehensive way, conventional radiocarbon ages obtained by older studies are still of value after they have been converted using modern calibration tools (Hogg et al. 2013; Reimer et al. 2013a, 2013b).

A process not yet fully implemented with the attempts to relate the horizontal position of fossil organic matter within lateral moraine profiles to former glacier surfaces and consecutively characterise magnitude or overall expansion of the glacier (cf. Röthlisberger 1986) is sediment aggradation leading to changing valley floor levels (see Fig. 2). Tasman Glacier is a good example where the remnant of the outermost neoglacial latero-frontal moraine ('Little Hump', c. 6,500 years old - Schaefer et al. 2009) exhibits an elevation more than 100 m lower than the proximal 'Little Ice Age' moraine. A reconstructed palaeo-glacier surface would consequently be at least 100 m lower than the 'Little Ice Age' one, despite the former supporting an advance roughly 700 m further downvalley. Unless Tasman Glacier's geometry has radically changed since formation of 'Little Hump', the strongest neoglacial advance could be represented by organic matter within the lowest parts of any lateral moraine upvalley and prone to misinterpretation as moderate or minor glacial expansion period only. Generally, the different nature of evidence requires caution with the amalgamation of radiocarbon and other numerical age records (see below) without concurrent detailed geomorphological assessment.

A major obstacle for the reconstruction of Holocene glacier chronologies solely based on direct glacial evidence in form of moraines and other glacial landforms constitutes, however, the problem of 'erosional censoring' (Kirkbride and Winkler 2012). If subsequent glacier advances become more extensive, they usually destroy any evidence of less extensive previous ones. This causes incomplete glacier records especially in those regions that experienced the 'Little Ice Age' as most extensive (late) Holocene advance. An alternative approach meanwhile developed into a method delivering very reliable and high-resolution records for Holocene glacier activity and their climate drivers is the study of glaciofluvial sediment in distal lakes (e.g. Dahl et al. 2003; Matthews and Dresser 2008; Wittmeier et al. 2015). When favourable environmental conditions allow successful execution, lake sediment studies bear the advantage of revealing also information about periods of smaller or even absent glaciers, thus adding to any direct evidence of glacier activity (cf. Kirkbride and Winkler 2012, Matthews 2013 for more detail on additional indirect approaches for the reconstruction of glacier chronologies).

1.3 The rise of surface exposure dating and aims of this study

It is not an exaggeration to claim that the investigation of Holocene glacier chronologies experienced a substantial boost or even almost a rejuvenation after progress within the field of surface exposure-age dating using in situ cosmogenic nuclides (TCND = terrestrial cosmogenic nuclide dating or CRN = cosmogenic radionuclide dating; cf. Dunai 2010; von Blankenburg and Willenbring 2014) saw this 'new' numerical dating technique applied on (late) Holocene moraines. TCND utilising ^{10}Be (and increasingly also ^{3}H, ^{14}C, ^{36}Cl) offers the sought-after opportunity to numerically date boulder and bedrock surfaces on glacier forelands that naturally often lack access to potential buried organic material for radiocarbon dating. A milestone was the work of Schaefer et al. (2009) in the Southern Alps of New Zealand with no less than 74 TCND-sampled moraine boulders in 3 glacier forelands. They achieve remarkable precision and small errors with their reported individual numerical ages. TCND as relatively new dating technique for Holocene glacier chronologies has seen astonishing progress during recent years including the intro-

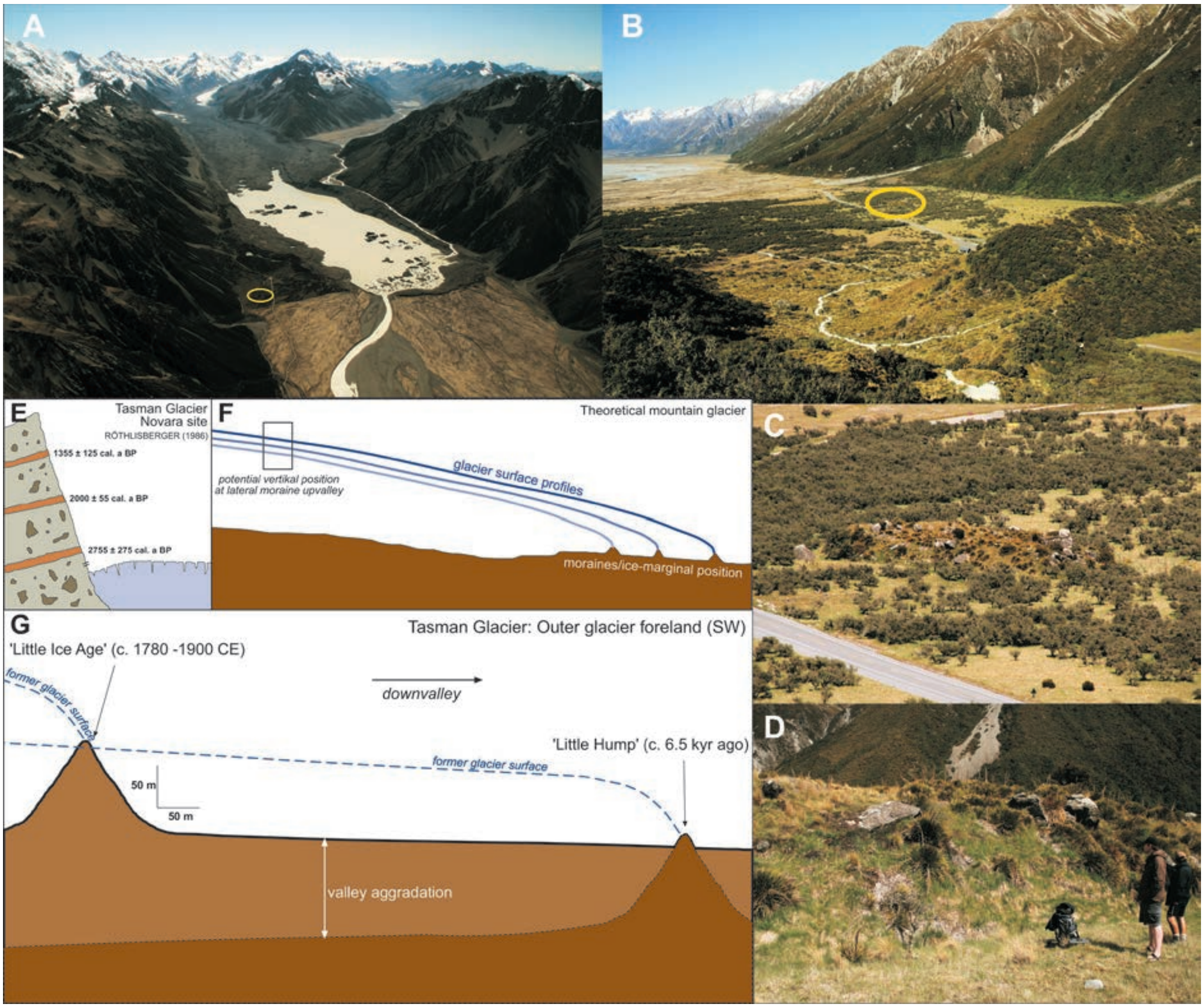

Fig. 2: Challenge of interpreting radiocarbon ages at Tasman Glacier: (a) Tasman Glacier's lower tongue and glacier foreland, the outermost neoglacial moraine 'Little Hump' (cf. text) is circled (26.02.2008); (b) 'Little Hump' (circled) as seen towards the South from the crest of the 'Little Ice Age' moraine (22.11.2017); (c) close-up (30.11.2015) and (d) ground view of 'Little Hump' (15.11.2011); (e) example of a lateral moraine profile with radiocarbon-dated buried organic matter (modified after Röthlisberger 1986); (f) theoretical relationship between frontal positions and palaeo-glacier surfaces as represented by buried organic matter in lateral moraine profiles at an ideal valley glacier and (g) actual situation in the southwestern foreland of Tasman Glacier due to significant valley floor aggradation (see text for further explanation).

duction of new production rates (cf. Putnam et al. 2010; Lifton et al. 2014; Borchers et al. 2016), accessible online calibration tools (Balco et al. 2008; Marrero et al. 2016; Phillips et al. 2016a, 2016b), laboratory preparation procedures (e.g. Corbett et al. 2016), or improved control on the necessity to apply correction for snow shielding (Benson et al. 2004; Schildgen et al. 2005; Delunel et al. 2014) to name just a few recent improvements.

But even if all this progress in near future certainly will help to further improve precision and tighten existing error bars, there is still an increasing source of concern unrelated to these more 'technical' aspects. Already Kirkbride and Winkler (2012) noted a sometimes subliminal 'overconfidence' in this dating technique combined with its apparent 'supremacy' over the results of other dating techniques and, most concerning, even the overall geomorphological context of the sampled sites. This geomorphological uncertainty, addressed and demonstrated with the help of a case study below, needs to be treated as the most serious source of uncertainty with the assessment of TCND-based glacier chronologies. It may largely exceed adjustments of perhaps ~5 % with the actual age estimates (hardly more) that seem possible in the light of new calibration tools and calibration procedures currently under development. Because many TCND studies focus much less than older work on an initial geomorphological mapping and analysis or sometimes seem to 'hide' such information in supplementary data files, this is a regrettable development. Further problems arise when such data records are collected for global compilations or online data bases to perform subsequent chronological or palaeoclimatic investigations, simply because details on possible geomorphology-related uncertainties may likely become lost.

It is the aim of this plea to argue for the unchanged value of an initial and rigorous geomorphological analysis of glacier forelands during every investigation of Holocene glacier chronologies – even in the light of abovementioned considerable progress with numerical dating techniques. By focusing on a frequently cited key site and a well-known study indisputably constituting a methodological benchmark the potential consequences of ignoring geomorphological uncertainties will empirically be demonstrated to raise awareness of this issue. Despite recent attempts to solve inconsistencies related to the interpretation of numerical age estimates by using statistical measures (Applegate et al. 2010, 2012; Heyman et al. 2011, 2016; Dortch et al. 2013) it will be shown that addressing the underlying geomorphological fundamentals during chronological investigations may be an easier and more reliable solution to tackle any emerging discrepancies. Finally, potential consequences of not accepting the 'supremacy' of glacial geomorphology with the reconstruction of Holocene glacier fluctuations and their subsequent palaeoclimatic interpretation will be outlined briefly.

2 The study site – Mueller Glacier

2.1 Natural environment in the Southern Alps

The Southern Alps with their peaks and ranges of 3,000 m a.s.l. and higher are the dominating relief structure of New Zealand's South Island (Fig. 1). The Main Divide extends parallel to its western coastline often in less than 30 km distance and is responsible for orographically controlled precipitation with a strong west-east gradient (Chinn et al. 2005). Annual precipitation in this maritime mid-latitudinal climate rises from 3,000 mm at the coast to 10,000 mm (and possibly more) at the glacier's accumulation areas west of the Main Divide, before it drops sharply east of it (Griffith and McSaveney 1983). But despite the lack of long-term precipitation data from high elevations, short-term studies indicate that glaciers immediately to the east of the Main Divide within the current centre of glaciation can still be characterised as maritime and benefit from so-called 'overspill' (Chinn et al. 2008; Winkler et al. 2010). Summer snow fall events are quite common in accumulation areas and snow fall down to 1,000 m a.s.l. or lower connected to extreme weather events may occur all year. This substantial precipitation constitutes a requirement for glaciers to exist within the Southern Alps that display a relative equator-ward position for mid-latitudinal mountain regions with comparatively mild annual air temperatures. Broad glacier accumulation areas above 2,000 m a.s.l. are concentrated near Southern Alps' highest summit Aoraki/Mt. Cook (3,724 m a.s.l.), but until very recently glacier termini could flow as far down-valley as 300 m a.s.l. towards the West and 750 m a.s.l. towards the East (Winkler 2015b). Corresponding mean annual air temperatures are estimated to c. 11°C (Franz Josef Glacier, 300 m a.s.l.) and c. 8.5°C (Mt.Cook Village, 800 m a.s.l.). The New Zealand glacier inventory compiled during the 1970s lists 3,132 individual glaciers and a total of 1,139 km^2 glacier area (Chinn 1989; Hoelzle et al. 2007). The total ice mass has since decreased from 54.5 km^3 (1976) to 46.1 km^3 (2008) with a significant bias of loss contributed by 12 large debris-covered glaciers with proglacial lakes (70 %; Chinn et al. 2012). An updated inventory (Baumann et al. 2017) reports a glacier area of 857 km^2 for 2016 derived from remote sensing data.

Their tectonic setting and high neotectonic activity in combination with frequent climatic extreme events are main factors for highly dynamic geomorphological process systems in the Southern Alps characterised, amongst others, by frequent mass movement events of high magnitude (for details see Korup et al. 2005; Cox and Barrell 2007; Davies 2016). As a consequence, supraglacial debris-cover constitutes a regionally important glaciological factor. Although supraglacial debris input to the glacier transport system is high for most glaciers of the Southern Alps (Hambrey and Ehrmann 2004), the potential impact on moraine formation processes or glacier behaviour in this extreme geomorphic environment has only be discussed recently, and mostly connected to the particular case of Late Glacial Waiho Loop moraine at Franz Josef Glacier (cf. Shulmeister et al. 2009; Reznichenko et al. 2012a, 2012b). With the investigation of Holocene glacier chronologies in the Southern Alps, influence of highly dynamic geomorphological processes has to be accepted and the resulting uncertainties have to be addressed with the palaeoclimatic interpretation of any landform (Reznichenko et al. 2016). This will be demonstrated below by geomorphologically assessing the results of Schaefer et al. (2009) from Mueller Glacier in Aoraki/Mt. Cook National Park. This glacier is a good example for the larger valley glaciers close to the Main Divide with a length of 13.9 km and an area of 22.5 km^2 according to the 1970s glacier inventory (Chinn 1996). Frontal retreat in combination with continuous growth of its emerging proglacial lake has shortened its length and decreased its area since (see Fig. 3).

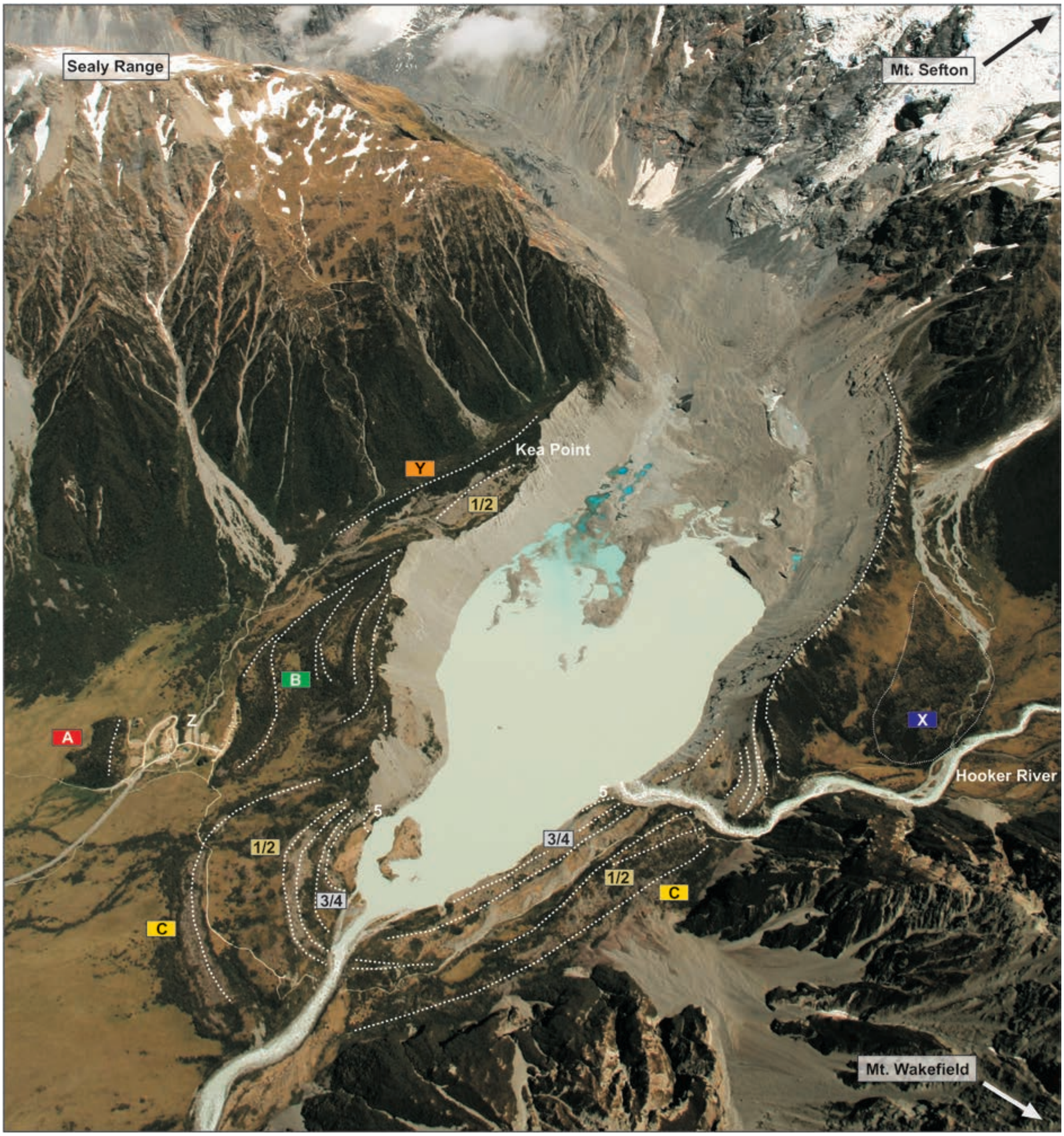

Fig. 3: Oblique air photo of Mueller Glacier and its foreland (08.12.2010). Moraine ridges are labelled following Winkler (2000) and the colour-coding corresponds to the one partially used with Figures 7, 9 and 10. A few other features (see text) are indicated including the position of Mt. Sefton (= Main Divide of the Southern Alps). The proglacial Mueller Lake has further enlarged since the photo was taken and the heavily supraglacial debris-covered glacier tongue retreated accordingly (cf. also Figure 5).

2.2 Previous chronological studies

New Zealand's Southern Alps are considered one of the rare key localities in the Southern Hemisphere for the investigation of Holocene glacier chronologies. Their position within the southern mid-latitudinal climate zone furthermore will potentially provide valuable insights into temporal changes of the atmospheric circulation patterns of the whole Australian-Southwest Pacific sector. Until more recently (cf. Davis et al. 2009), their palaeoclimatic potential was not satisfactory utilised, perhaps a result of disagreement between several studies that had been carried out during the past decades applying different approaches and dating techniques (cf. summaries in Röthlisberger 1986; Gellatly et al. 1988; Burrows 2005; Winkler 2005). With this background, the groundbreaking work of Schaefer et al. (2009) offering a novel approach to precisely numerically date moraines by TCND was well received. Apart from the above-mentioned methodological progress, the study by Schaefer et al. (2009) also provides a new major conclusion contrasting to Röthlisberger's (1986) previous view of globally parallel glacier fluctuations by stating that the Holocene glacier chronology in New Zealand differs from the Northern Hemisphere. The latter statement attracted criticism by Winkler and Matthews (2010a) highlighting that Schaefer et al. (2009) do not provide a representative sample of Northern Hemispheric chronologies for their comparison because they do not consider Scandinavia and other maritime regions. Later, the same group (Putnam et al. 2012) performed a similar study at Cameron Glacier (Arrowsmith Range) and amalgamates both records as 'regional' glacier chronology that basically constitutes the undisputed frame of the 'New Zealand' record as presented by Solomina et al. (2015, 2016). However, different climatological and glaciological properties alongside a lack of corresponding glacier advances during the late Holocene (cf. Fig. 10) do not convince that this merger of local chronologies is fully justified, as Winkler (2014) referring to requirements outlined by Kirkbride and Winkler (2012) pointed out. There is certainly need for further discussion of this issue, but to allow focus on the geomorphological assessment it will not be followed up here.

The precision and reliability of individual samples/^{10}Be ages (see Fig. 4) is undisputed and remains out of any discussion here. Because Schaefer et al. (2009) applied production rates from Balco et al. (2009) very similar to Putnam et al.'s (2010), any attempt to recalculate their ages using newer calculation tools (see above) would theoretically only result in minor changes of a few % and likely fall within existing error ranges. Therefore, their

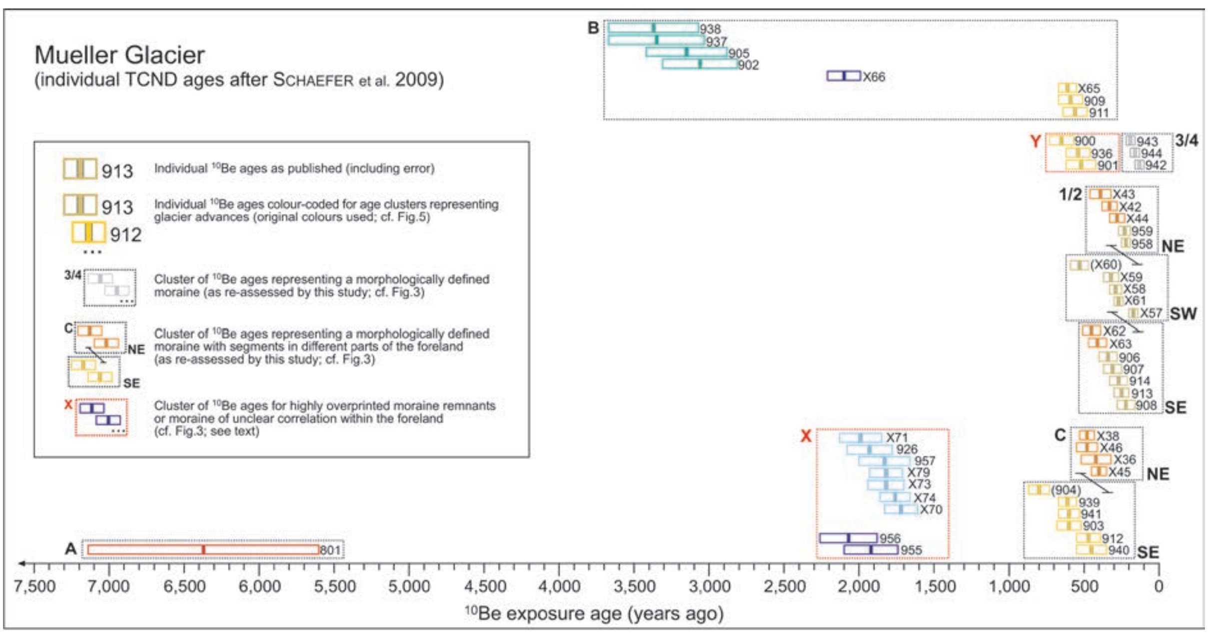

Fig. 4: Original ^{10}Be boulder ages for Mueller Glacier as reported by Schaefer et al. (2009). The colour-coding of individual samples illustrates their chronological interpretation as individual glacier advances on succeeding Figure 5. Sample X66 is displayed as part of the '2000 yr advance' like on Schaefer et al.'s (2009) original map. Two samples they regard as outlier (904, X60) are indicated by brackets. Please note few unavoidable differences to the morphological colour-coding used with Figures 3 and 9.

original data will be used here. Any recalculation effort would, furthermore, only refract from the overarching aim to highlight the geomorphological uncertainties and resulting consequences for the palaeoclimatic interpretation of Holocene glacier chronologies.

3 Dating moraines on the Mueller Glacier foreland

Schaefer et al. (2009) focused their study on Mueller Glacier and sampled 51 boulders in total on its foreland alongside 23 more at neighbouring Hooker and Tasman Glaciers. Apart from easy accessibility focus on Mueller Glacier is justified by its sequence of several moraines potentially representing an extensive if not complete chronology of (late) Holocene glacier advances. Detailed examination reveals, however, that appraisal of these glacial landforms as evidence for related glacier activity is not as straightforward as one may initially expect (cf. Burrows 1973; Winkler 2001, 2005; Reznichenko et al. 2016). Nevertheless, all ^{10}Be samples from Mueller Glacier including two Schaefer et al. (2009) classify as outliers (Fig. 4) are considered with this geomorphological re-assessment.

In their procedure to establish a chronology for Mueller Glacier's advances, Schaefer et al. (2009) at first cluster individual boulders sampled in different parts of the foreland on segments of moraine ridges or what appeared to be moraine remnants. Main criterion for establishing these clusters and any subsequent correlation of clusters in different parts of the foreland obviously were the ^{10}Be age estimates they obtained and not necessarily geomorphological or sedimentological criteria (see below). Reason for this rather unusual and unconventional approach may have been the complex configuration of Mueller Glacier's foreland and challenges with identifying corresponding moraine ridges in different parts of it. For example, White Horse Hill moraine complex (moraine B – see Figs. 3, 8) seems to have influenced glacier expansion after its initial deposition creating a division between the south-western foreland (at the so-called Kea Point) and its south-eastern counterpart. Finally, Schaefer et al. (2009) concluded that their ^{10}Be samples give evidence of 8 individual glacier advances of Mueller Glacier (Fig. 5). The ages for these advances each represented by 'moraines' are based on the arithmetic mean of all boulders within the corresponding cluster (see below).

4 Geomorphological interpretation of numerical boulder ages

Field experiments and selected tests have persuasively shown that the zero-age assumption (i.e. fulfillment of the 'no-inheritance' requirement) with the cosmogenic nuclide dating of rock fragments recently deposited at modern temperate glaciers is a valid one (Putnam et al. 2012; Schimmelpfennig et al. 2014; Matthews et al. 2017). Schaefer et al. (2009) come to the same conclusion, yet surprisingly miss to draw related consequences for the procedure to obtain their final age estimates for boulder clusters. If inheritance as factor yielding too old exposure ages apparently can be neglected with the dating of 'Little Ice Age' or historic moraines, the same should consequently apply to mid- and late Holocene moraines.

Despite no regional study explicitly focusing on details of moraine formation processes in the Southern Alps is known to the present author, there is no reason why established knowledge about lateral moraine formation at mountain glaciers predominantly driven by dumping of supraglacial debris (cf. Humlum 1978; Winkler and Hagedorn 1999; Lukas et al. 2012; Baumhauer and Winkler 2014) cannot be transferred to the dominant lateral moraines on the glacier forelands of Aoraki/Mt. Cook National Park (see Figs. 2, 6). Abundance of supraglacial debris especially on the lower glacier tongues and related debris pathways (cf. Kirkbride 1995; Hambrey and Ehrmann 2004) suggest that dumping also plays an important role with moraine formation in latero-frontal positions and even with terminal moraines. Sedimentological evidence in form of angular clasts and huge boulders is omnipresent (cf. Winkler 2001; Reznichenko et al. 2012b, 2016). Therefore, the mode of terminal moraine formation is different to the one observed during recent glacier advances in Southern Norway where previously deposited boulders were pushed up by a process described as bulldozing, some with lichens on their surface that survived the process and may be seen as an analogue to 'inheritance' here (see details in Winkler and Nesje 1999; Winkler and Matthews 2010b). Similar processes have been observed during recent advances at Fox and Franz Josef Glaciers (Winkler 2009), but additionally dumping of supraglacial debris occurred. Both glaciers exhibited no substantial supraglacial debris cover and are no suitable models for glaciers near Aoraki/Mt. Cook. A transport period of a few decades on the glacier surface prior to subsequent deposition along the glacier margins seems to be the only potential source of inheritance at the study sites.

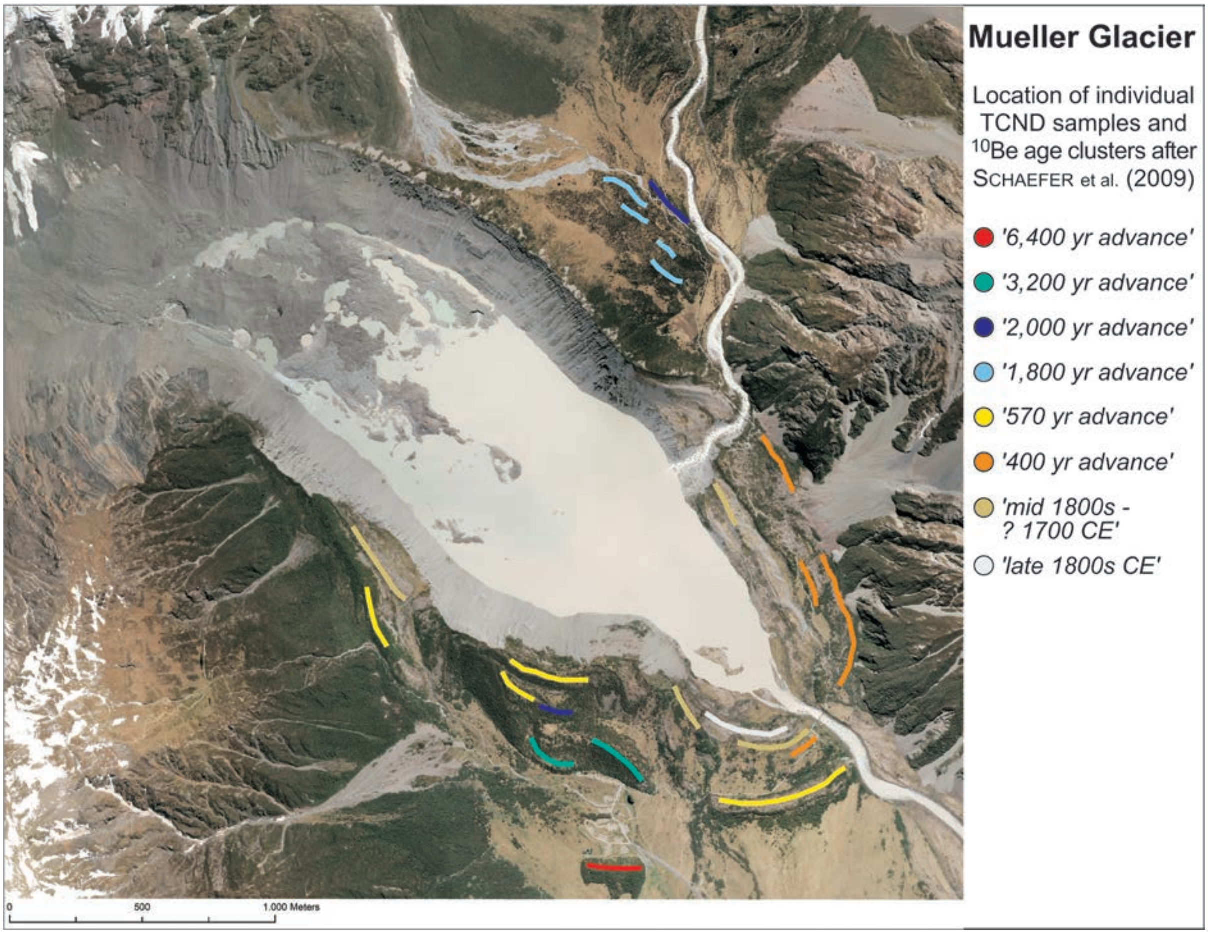

Fig. 5: Location of individual ^{10}Be boulder ages taken from Schaefer et al. (2009), colour-coded identical to their original map and on Figure 4 (Base map: Orthorectified aerial photo from early 2016 modified after Land Information New Zealand).

Applying realistic error margins with the TCND ages and subsequent chronological interpretation of individual boulders, this potential 'inheritance' may be ignored with reasonable justification.

By contrast to potential 'inheritance' yielding too old age estimates, there are several factors potentially yielding too young surface exposure ages for boulders sampled on Mueller Glacier's foreland. The model of formation presented by Reznichenko et al. (2016) for moraine C includes a core of dead glacier ice underlying a thick boulder carapace that will subsequently melt and cause disturbance or redistribution of boulders for certain time after final culmination of the glacier advance. The existence of temporary ice-cores in moraines at glaciers with considerable supraglacial debris cover is not uncommon (cf. Benn et al. 2005; Benn and Evans 2010) and cannot *a priori* be excluded with other moraines here as well. Steep slopes and less compacted material deposited by dumping leaves lateral moraines prone to paraglacial overprinting with significant erosion currently present (Fig. 6; cf. Blair 1994; Winkler 2015a). The abovementioned dynamic geomorphological process systems of the Southern Alps offer a wide range of possible processes that may disturb initial deposition of boulders on moraine ridges, from co-seismic displacement to the influence of (glacio)fluvial erosion or exhumation of initially buried boulders by slope erosion. This aspect of post-depositional modification of moraines and glacial sediments has already been well outlined in earlier work (e.g. Burrows 1973; Gellatly 1982). Summarising, detailed geomorphological analysis of the existing landforms on the glacier forelands including their potential modes of formation provides sufficient evidence (or at least hints) that post-depositional disturbance may potentially cause too young surface exposure ages in some cases.

The common practice of calculating arithmetic means for multiple boulder samples to gain an age estimate for the investigated moraine was also applied by Schaefer et al. (2009) at Hooker, Mueller, and Tasman Glaciers. It may well be legitimate prac-

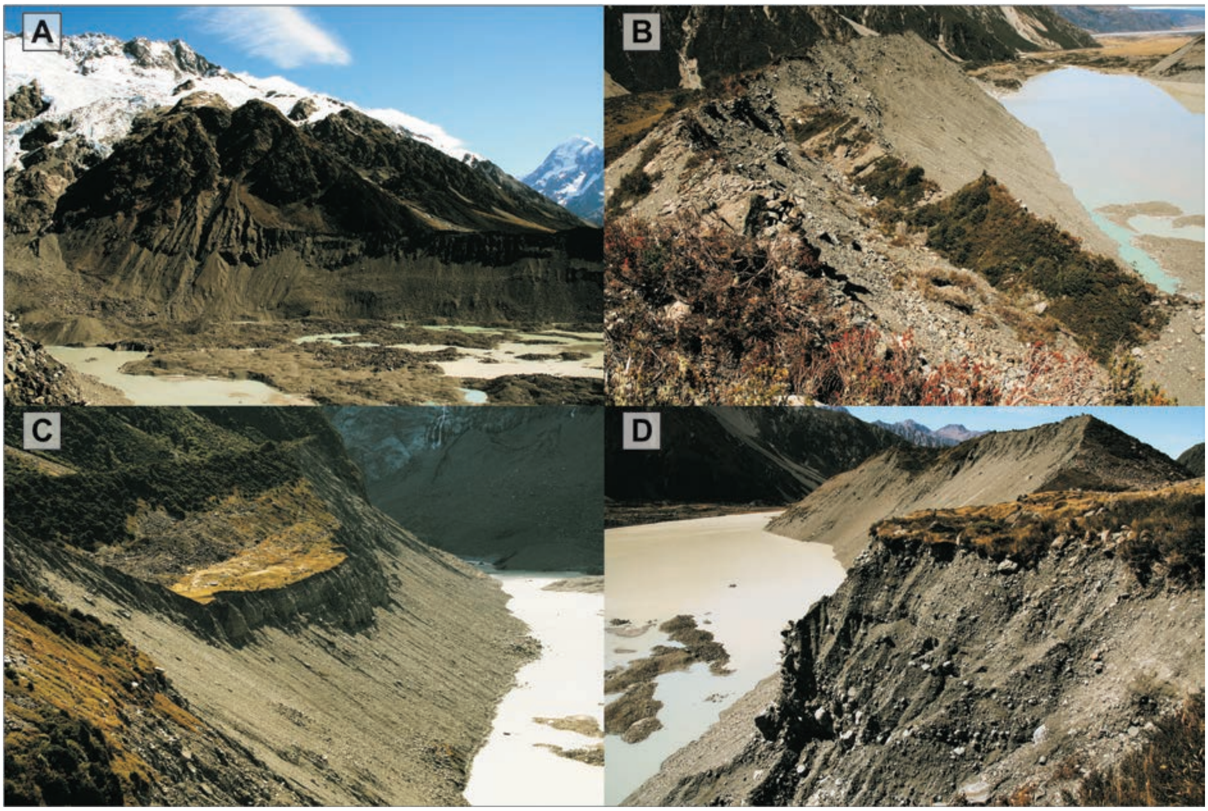

Fig. 6: Lateral moraines and paraglacial activity at Mueller Glacier: (a) North-eastern lateral moraine with Mt. Sefton (29.02.2017); (b) proximal slope of the north-eastern lateral moraine showing a part of its crest recently slumped down – a mechanism potentially causing problems with any subsequent investigation of buried organic material in moraine profiles (cf. Fig. 2; 22.03.2018); (c) proximal south-western foreland and Kea Point as seen from moraine B (23.02.2018); (d) proximal slope of moraine B and erosional scarp at Kea Point (20.02.2017).

tice if obtained ages cluster closely or local factors potentially resulting in too old or too young ages (i.e. outliers) are assessed as equally-weighted. Whereas Winkler (2014) used the mean of 8 closely clustered ^{10}Be ages on the outermost 3 ridges of a lateral moraine sample at Strauchon Glacier (Western Southern Alps) to date a 'LIA'-type event to around 2,800 years ago (mean 2,817 years, σ 156 years or 5.5 %), comparable values for the south-eastern segment of moraine C at Mueller Glacier calculated after Schaefer et al.'s (2009) raw data would be a mean of 588 years with a σ of 125 years or 21.3 %. Clearly, the spread of individual ages for some moraines at Mueller Glacier (cf. Fig. 4) seems too wide to justify the use of arithmetic means or, alternatively, median values for final moraine dating.

The case of Mueller Glacier's moraine C is an alerting example highlighting this problem (see Fig. 7). Ultimately the detailed study of Reznichenko et al. (2016) confirmed earlier suspicions (Winkler 2000, 2005) and demonstrates that moraine C with its unique lithological, morphological, and sedimentological signature among all moraines at Mueller Glacier constitutes evidence for one accurately defined marginal position (and glacier advance) only. By contrast, Schaefer et al. (2009) assign its south-eastern and north-eastern segments to two different 'moraines' (their '570 yr' and '400 yr advances', respectively; cf. Figs. 5, 7a). Splitting moraine C likely is the result of their practice to use arithmetic means because if both segments are treated separately, they yield non-overlapping results. But if all individual boulder ages for both segments are considered as one sample (i.e. acknowledging geomorphological reality that it constitutes one moraine), the ages overlap fairly well except for the south-eastern segment also including some older ages (Fig. 7b). Interestingly, previous relative-age dating studies (lichenometry, Schmidt-hammer relative-age dating; Winkler 2000, 2005) noted slightly younger ages in the north-eastern foreland and suggested, alongside micro-climatic factors, possible post-depositional disturbance. In fact, the proximity to the active slopes of Mt. Wakefield opens for possible impacts

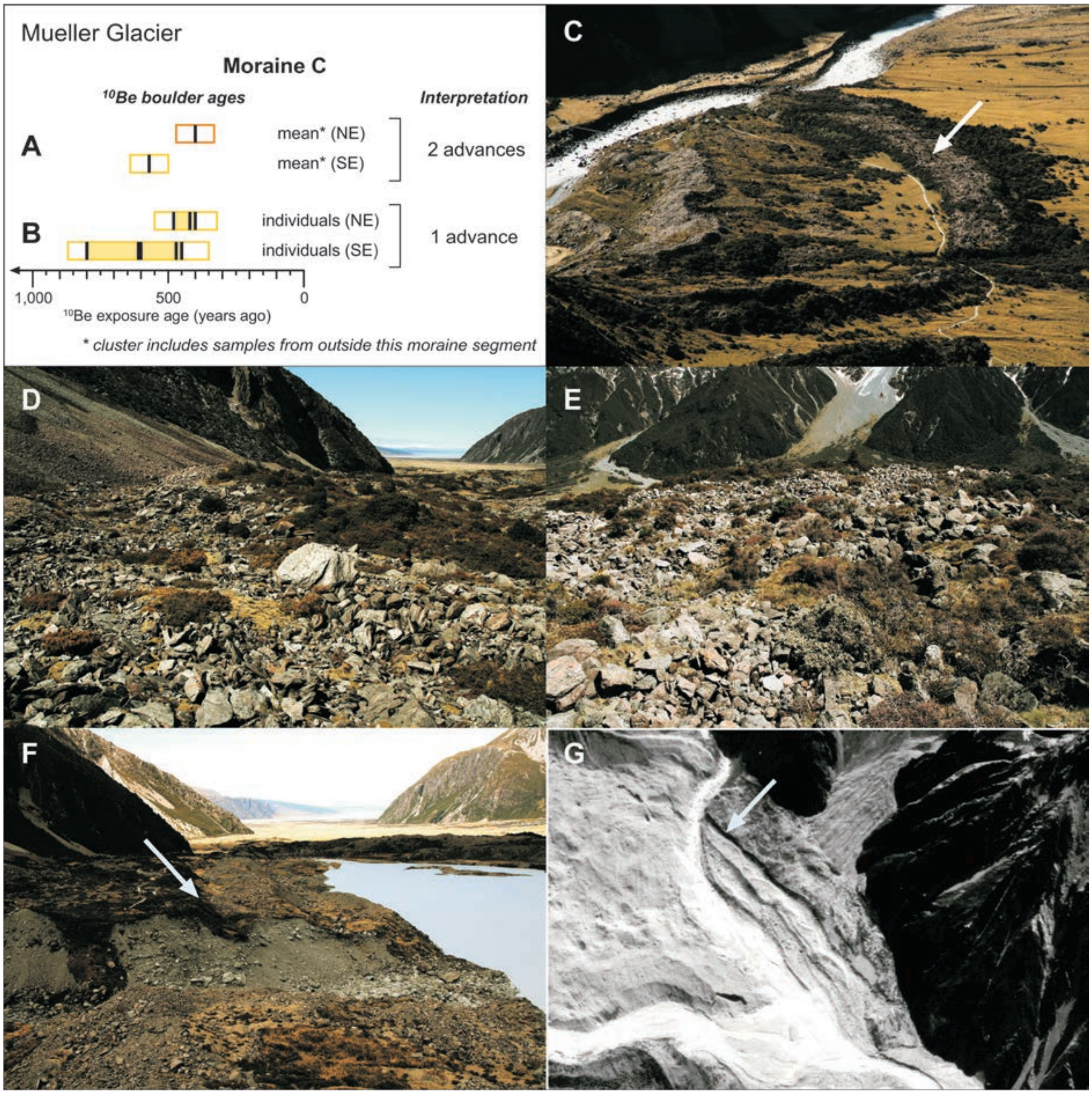

Fig. 7: Moraine c at Mueller Glacier: (a) ^{10}Be ages for moraine C originally interpreted as 2 segments related to different advances (Schaefer et al. 2009) and (b) alternatively based on evidence provided by Reznichenko et al. (2016) as representing one moraine only (cf. text and Fig. 5); (c) moraine C (arrow) from Sealy Range (24.03.2008); (d) surface of the north-eastern segment towards the South (04.11.2012); (e) surface of the south-eastern segment towards Sealy Range (03.11.2013); (f) glaciofluvial terrace edge (arrow) in the north-eastern foreland from the north-western lateral moraine (21.02.2017) and (g) on an aerial photo from March 1960 (modified after New Zealand Aerial Mapping).

of mass movement processes and snow avalanches (see Fig. 3). Furthermore, it has been reported that Hooker River draining the upper Hooker Valley once flew subglacially below the easternmost tongue of Mueller Glacier during the late 19th century (Gellatly 1985). During periods Mueller Glacier extended as far as the base of Mt. Wakefield's slopes the only alternative for Hooker River apart from any supra-, en-, or subglacial course would have been a marginal channel alongside Mueller Glacier's north-eastern tongue. Erosional terrace risers provide evidence that this happened at least during the 'Little Ice Age' (see Fig. 7f, 7g). It seems, therefore, very likely that during earlier late Holocene advances of Mueller Glacier glaciofluvial erosion was a potential cause of post-depositional disturbance with any moraine ridged formed in the north-eastern part of its foreland.

5 Geomorphological re-assessment of moraines

If moraines as landforms intrinsically linked to changes of glacier margins are utilised as palaeoclimatic record, the nature and mechanisms of climate variability driving the underlying glacier's mass changes need to be understood. It is, however, equally important to ensure the integrity of its moraines representing geomorphological evidence of glacier length and marginal position changes. Any moraine not unambiguously identified as such or not distinctively representing a former ice-marginal position needs to be flagged and excluded from any attempt to reconstruct the chronology for the selected glacier (Kirkbride and Winkler 2012). Another recommendation is to geomorphologically map the glacier foreland and surrounding landforms. It allows verified reconstruction of former ice-marginal positions as well as identification of corresponding moraine ridges in different parts of the glacier foreland. For accuracy and reliability of subsequent analyses it is essential that this task is performed without any influence of or bias against available chronological information. The geomorphological integrity of a moraine representing a certain ice-marginal position needs to become higher ranked than the results obtained by application of any chosen dating technique, because none of the latter can *a priori* be assumed to be free of potential methodological error. Even with Schaefer et al.'s (2009) work being frequently rated as 'benchmark' by subsequent studies, one should not refrain from anticipating high standards regarding the abovementioned geomorphological context.

Detailed geomorphological analysis of glacial landforms on the Mueller Glacier foreland reveals more than one case of discrepancy between the straight morphological correlation of moraine segments or their genetic interpretation and ^{10}Be boulder age clusters seen as evidence of glacier advances and labelled 'moraines' by Schaefer et al. (2009). In geomorphological as well as in chronological context their two youngest 'moraines' are, however, unproblematic. These 'Little Ice Age' and historic moraine ridges (labelled by numbers on Fig. 3) have previously been dated using modern lichenometric approaches yielding comparable results (cf. Winkler 2000; Lowell et al. 2005). In the south-western foreland, the moraine ridge labelled Y (Figs. 3, 8a) constitutes the outermost lateral moraine and extends from Kea Point along the base of the northernmost Sealy Range for a few hundred meters before it disappears due to erosion by a large, still active fan. Close to its southern end, it becomes double-ridged for a short distance. Without any obvious continuation it is difficult to link this otherwise typically shaped moraine segment to any other feature on the foreland. Based on the best fit for the ice margins of a conventionally shaped glacier tongue (see Fig. 5) it could line up with Foliage Hill (moraine A) or a low diffuse patch of morainic material (a moraine remnant heavily modified by glaciofluvial action?) between Foliage Hill and White Horse Hill (marked Z on Figs. 3, 8a). Despite a younger glacial meltwater outburst has created a marked depression and overprinted the western end of White Horse Hill, the layout of moraine ridge Y does not match with any of the outer individual ridges on White Horse Hill. From a morphological point of view, moraine Y needs to be formed prior to White Horse Hill, but it is part of the '570 yr moraine' by Schaefer et al. (2009) whereas the oldest ridges on White Horse Hill are dated to 3,200 years ago. The ^{10}Be age provided for moraine ridge Y (cf. Tab. 1, Fig. 9) is, therefore, contradictory to the geomorphological situation.

A hummocky area distal to the prominent lateral moraine in the north-western foreland of Mueller Glacier (labelled as X on Fig. 3) is interpreted as constituting moraine remnants and linked to two advances by Schaefer et al. (2009). Despite a substantial number of huge boulders in the area and its absolutely likely origin as moraine(s), it is hard to identify any distinct moraine ridges within (Figs. 8e, 8f). Furthermore, the meltwater stream from Stocking/Te Wae Wae Glacier cuts through it and separates the part that should match the '2,000 yr moraine' from the southern one constituting Schaefer et al.'s (2009) '1,800 yr moraine' (cf. Fig. 5). Without clear moraine ridges present in the area, how reliable are ^{10}Be ages obtained from boulders within for any glacier advance? To classify surface exposure ages as reliable the sampled boulders neither must have been disturbed by any post-depositional action nor exhumed by slope erosion following initial moraine formation. The whole area X appears highly overprinted and if boulders should be of glacial origin (what seems quite likely), they need to have been deposited prior to the proximal prominent lateral moraine. But without distinct moraine ridges or moraine remnants exhibiting unquestionable undisturbed boulders, all ^{10}Be ages of area X can be interpreted as (random) minimum ages only and not as evidence of two separate glacier advances.

As described above in detail, moraine C constitutes an individual moraine and assigning it to two different moraines by Schaefer et al.'s (2009) is likely an artefact of their age calculations procedure ultimately foiling geomorphological, lithological and sedimentological facts (Reznichenko et al. 2016).

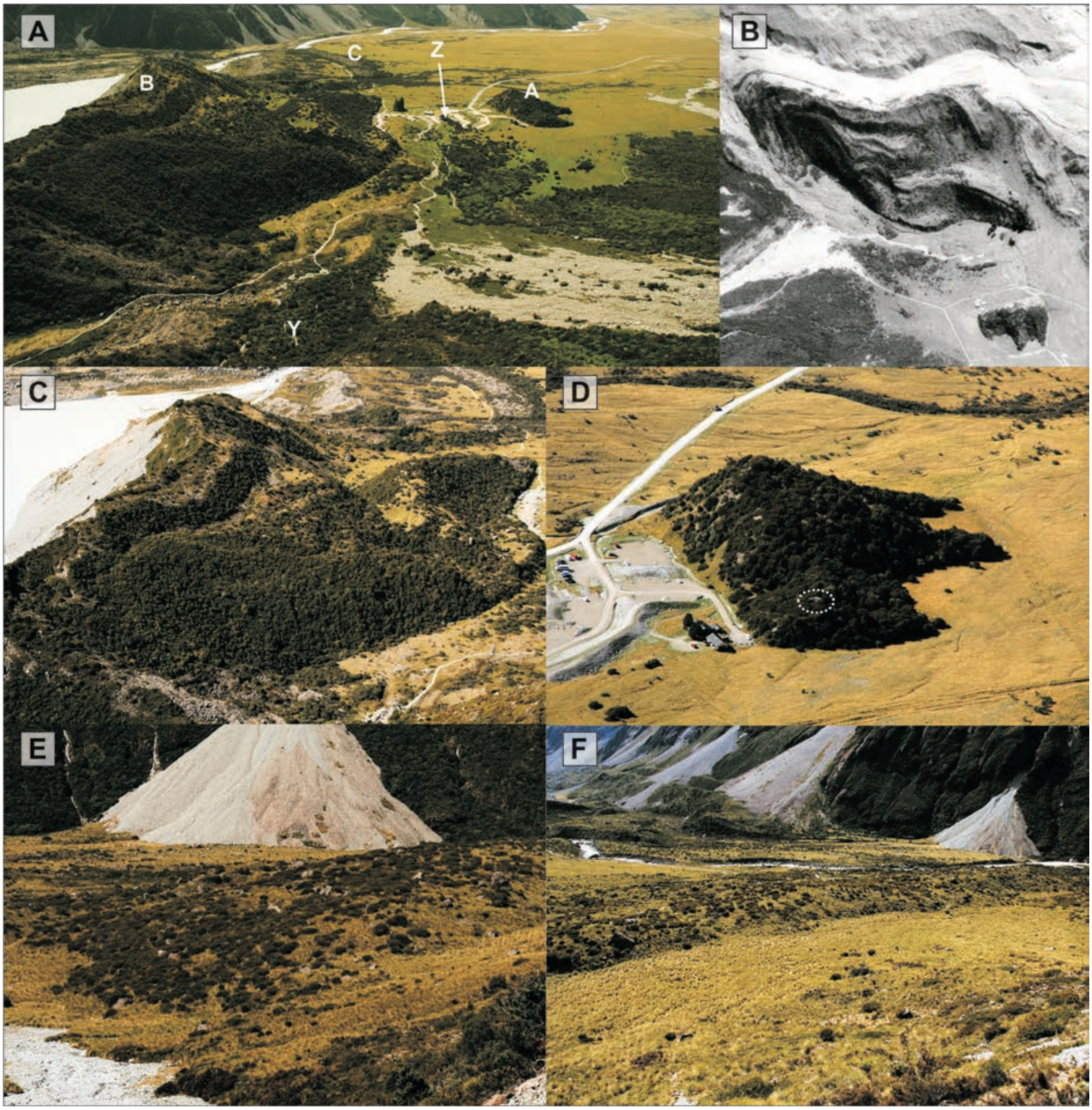

Fig. 8: Moraines on the Mueller Glacier foreland: (a) View from Sealy Range towards the southern foreland (25.11.2011; cf. Fig. 3 and text for labelled features); (b) White Horse Hill on an aerial photo from March 1960 (modified after New Zealand Aerial Mapping); (c) White Horse Hill (24.03.2008); (d) Foliage Hill with boulder (circled) sampled by Schaefer et al. (2009; 24.03.2008); (e), (f) morainic area (labelled X on Fig. 3) distal to the north-western lateral moraine (23.02.2018, 24.02.2018).

By contrast, all studies following Lawrence and Lawrence (1965) unanimously interpreted Foliage Hill as moraine or moraine remnant, respectively. Its position (see Figs. 3, 8a) and sedimentology leaves little doubt. Its detailed shape points, however, towards at least some modification of its original moraine ridge morphology. There is no clear ridge crest parallel to the assumed former glacier margin in W-E direction but two ravines perpendicular to it trending southwards (Fig. 3). The height of Foliage Hill in parallel to the assumed glacier margin is variable and the solely boulder sampled by Schaefer et al. (2009) sits on its western end lower than the highest parts of the crest (Fig. 8d). With this location in relation to the morphology of Foliage Hill one cannot rate the sampled boulder as immune to any post-depositional disturbance despite its ^{10}Be age corresponding well with a moraine remnant at Tasman Glacier ('Little Hump'; s. Figs. 2, 10). Nevertheless this conclusion bears the danger of too optimistic 'lumping'. It would be the only pre-'Little Ice Age' advance of Schaefer et al.'s (2009) study that had left evidence at more than one individual glacier. Finally, White Horse Hill displays an unusual morphology in form of its substantial base width and moraine ridges that seem rather 'superimposed', especially the ones on its lower, southern slopes (Figs. 8b, 8c). It would be tempting to scrutinise the reason for its specific morphology that could well reveal a 'core' in form of a glacially displaced massive rock avalanche or landslide deposit. But until conflicting evidence will emerge, the most sensible interpretation for it is a moraine system shaped and modified during possibly more than one glacier advance.

6 Consequences for glacier chronology and subsequent correlation

As mentioned above, applying the ^{10}Be age obtained from the oldest individual boulder rather than arithmetic means seems a legitimate alternative for final dating of moraines at Mueller Glacier given the dynamic geomorphological environment of the Southern Alps. It may additionally be argued on well-founded basis that geomorphological problematic boulder clusters and moraines not clearly linked to a glacier advance should preferably at first be excluded from any local glacier chronology. At Mueller Glacier, this would apply to the possible moraine remnants in area X and moraine ridge Y (cf. Figs. 3, 8). In any case, moraine C needs to be treated as one distinct moraine only and its segments not split into two 'moraines' as demonstrated above (Fig. 7). An alternative approach is to exclusively take clearly identified, uniform moraine ridges into account and re-cluster boulders accordingly (cf. Fig. 9, Tab. 1).

As shown on figure 9, the alternative attempt to outline Mueller Glacier's (late) Holocene glacier chronology based on Schaefer et al.'s (2009) original raw data but geomorphologically re-assess their ^{10}Be boulder ages provides considerable differences to their original chronological interpretation. Most remarkable is the apparent reduction of outlined pre-'Little Ice Age' glacier advances even if Foliage Hill remains part of the chronology due to its good correlation to the contemporaneous advance at Tasman Glacier ('Little Hump', see above). If the well-established concept of 'LIA'-type events sensu Matthews and Briffa (2005) rather than the concept of separate advances at individual glaciers is applied, there seems increased correlation between Hooker, Mueller, and Tasman Glaciers as well as some potential agreement between the available (late) Holocene TCND-based glacier chronologies in the Southern Alps (Fig. 10). Although there is no room for exploring these findings further at this early stage, the effect of a critical review including a geomorphological re-assessment of the glacier chronology at Mueller Glacier becomes more than obvious. It certainly will give inspiration for future work due to resulting consequences for global compilations and palaeoclimatic interpretation that to date mainly consider Schaefer et al.'s (2009) unaltered original chronology.

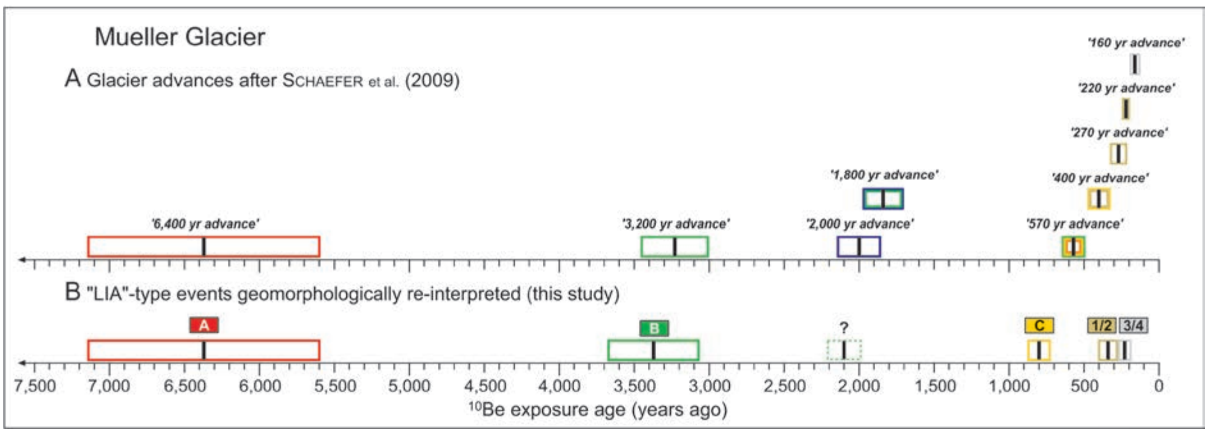

Fig. 9: (A) Glacier advances at Muller Glacier as originally outlined by Schaefer et al. (2009) compared to (B) 'Little Ice Age'-type events based on their raw data after geomorphological re-assessment (this study; cf. text). The colour-coding of part A refers to chronological boulder clusters as displayed on Figures 4 and 6 and indicates if ^{10}Be samples from different site have been amalgamated. For part B, the oldest individual ^{10}Be age (cf. Tab. 1) has been selected and all problematic moraine remnants have been excluded (see text for details). The single date (with question mark) represents a sample from moraine B that, unlike the ones from area X, morphologically could well represent a subsequent advance. Lichenometric ages for the 'Little Ice Age' and historic moraines (moraines 1 – 5; see Fig. 3) can be obtained from Winkler (2000) and are not considered with this purely TCND-based chronology here. Therefore, the original combination of Schaefer et al. (2009) in 1/2 and 3/4 has been retained (cf. Tab. 1).

Tab. 1: ^{10}Be ages used for calculation of the glacier chronology at Mueller Glacier as displayed on Fig. 9 (see text for details).

Site	Interpretation: *(Schaefer et al. 2009)* mean ^{10}Be age	oldest ^{10}Be age	Interpretation: *(this study)* oldest ^{10}Be age
Foliage Hill	6,520 ± 360 yr [(1)]	6,370 ± 760 yr	6,370 ± 760 yr
White Horse Hill	3,230 ± 220 yr 2,100 ± 100 yr 570 ± 70 yr*	3,370 ± 290 yr *one sample* 610 ± 50 yr	3,370 ± 290 yr *(2,100 ± 100 yr)?*
Moraine C	570 ± 70 yr* 400 ± 70 yr*	800 ± 60 yr 480 ± 40 yr	800 ± 60 yr
Moraine1/2	270 ± 50 yr 220 ± 10 yr*	340 ± 50 yr 230 ± 30 yr	340 ± 50 yr 1725/40 CE (lichen.)[(2)]
Moraine 3/4	160 ± 30 yr*	190 ± 20 yr	230 ± 30 yr 1860/95 CE (lichen.)[(2)]
Moraine ridge Y	570 ± 70 yr	650 ± 70 yr	*(650 ± 70 yr)?*
Morainic area X	2,000 ± 150 yr 1840 ± 130 yr	2,070 ± 180 yr	*(2,070 ± 180 yr)?*

(1) If combined with 'Little Hump' moraine from Tasman Glacier (see text)
(2) Lichenometrical ages after Winkler (2000)
* Includes samples from different moraines (cf. Figs. 4, 5)

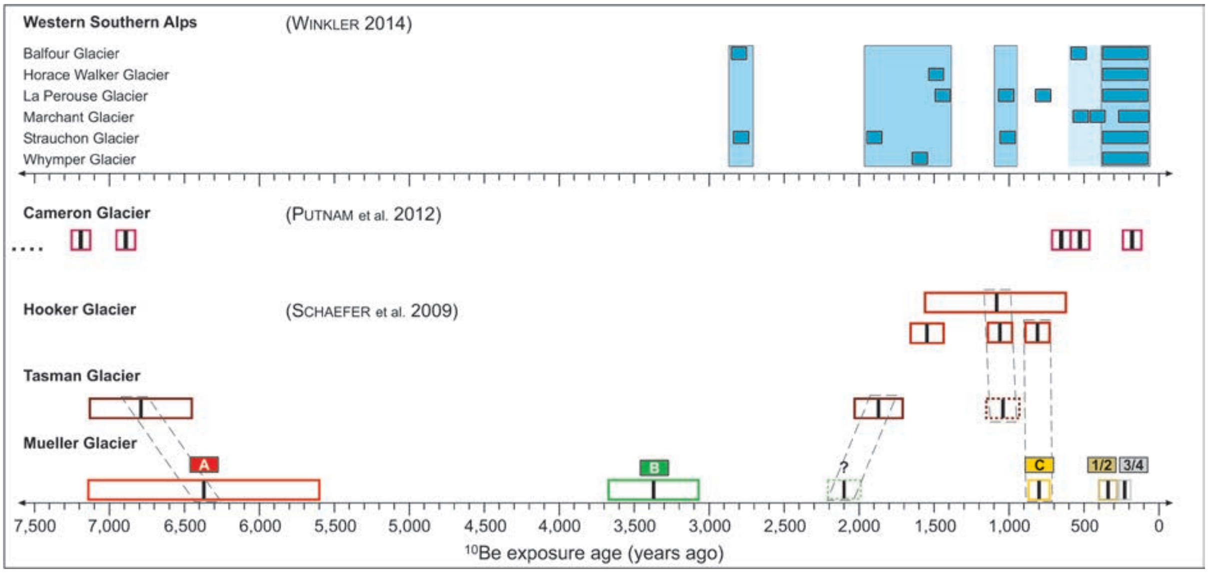

Fig. 10: Comparison of TCND-based chronologies for the Southern Alps. 'LIA'-type events from 6 glaciers in the western Southern Alps (Winkler 2014) are compared to the re-assessed chronologies for Mueller Glacier (cf. Fig. 9) and the neighbouring Hooker and Tasman Glaciers by Schaefer et al. (2009), both re-assessed in a comparable way here. The data from Putnam et al. (2012) from Cameron Glacier is only displayed for the overlapping period, i.e. excluding its multiple early Holocene advances.

7 Conclusions

Regardless of the desirable effort to further improve our ability to precisely and accurately numerically date moraines or other glacial landforms and increasingly execute multi-proxy approaches with the research on Holocene glacier chronologies, detailed geomorphological assessment of any glacier foreland investigated is indispensable. Furthermore, any arising discrepancy between individual moraine morphology or outline and related chronological information firstly needs to be considered as inaccuracy or failure of the dating attempt. Geomorphology needs to retain its undisputed 'inherent' supremacy over dating attempts it sometimes seems to have lost as a consequence of recent progress with numerical dating techniques alongside their increased specialisation, complexity, and laboratory expenditure. Sampling non-representative sites or material still seems to be the largest potential source of error as previously lamented by Kirkbride and Winkler (2012). Their recommendations for subsequent correlation and palaeoclimatic interpretation still are up-to-date. Especially as improved data availability encourages compilations of Holocene glacier chronologies on hemispheric and global scales, more critical reviews seem inevitable to avoid uncertainties caused by contextual negligence of (field) geomorphology.

References

Alean, J. (2010): Gletscher der Alpen. Bern.

Applegate, P. J.; Urban, N. M.; Laabs, B. J. C.; Keller, K. and Alley, R. B. (2010): Modeling the statistical distributions of cosmogenic exposure dates from moraines. In: Geoscientific Model Development 3, 293–307. https://doi.org/10.5194/gmdd-2-1407-2009

Applegate, P. J.; Urban, N. M.; Keller, K.; Lowell, T. V.; Laabs, B. J. C.; Kelly, M. A. and Alley, R. B. (2012): Improved moraine age interpretations through explicit matching of geomorphic process models to cosmogenic nuclide measurements from single landforms. In: Quaternary Research 77, 293–304. https://doi.org/10.1016/j.yqres.2011.12.002

Bamber, J. L. and Payne, A. J. (eds.) (2004): Mass balance of the cryosphere. Observations and modelling contemporary and future changes. Cambridge.

Balco, G.; Stone, J. O.; Lifton, N. A. and Dunai, T. J. (2008): A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. In: Quaternary Geochronology 3, 174–195. https://doi.org/10.1016/j.quageo.2007.12.001

Balco, G.; Briner, J.; Finkel, R. C.; Rayburn, J. A.; Ridge, J. C. and Schaefer, J. (2009): Regional beryllium-10 production rate calibration for late-glacial northeastern North America. In: Quaternary Geochronology 4, 93 - 107. https://doi.org/10.1016/j.quageo.2008.09.001

Barry, R. G. and Gan, T. Y. (2011): The global cryosphere: past, present, future. Cambridge.

Baumann, S.; Anderson, B.; Mackintosh, A.; Lorrey, A.; Chinn, T.; Collier, C.; Rack, W.; and Purdie, H. (2017): Updating the New Zealand glacier inventory. In: AGU fall meeting abstracts C53D-03. https://agu.confex.com/agu/fm17/meetingapp.cgi/Paper/245643

Baumhauer, R. and Winkler, S. (2014): Glazialgeomorphologie–Formung der Landoberfläche durch Gletscher. Stuttgart.

Beniston, M.; Farinotti, D.; Stoffel, M.; Andreassen, L. M.; Coppola, E.; Eckert, N.; Fantini, A.; Giacona, F.; Hauck, C.; Huss, M.; Huwald, H.; Lehning, M.; López-Moreno, J.-I.; Magnusson, J.; Marty, C.; Morán-Tejéda, E.; Morin, S.; Naaim, M.; Provenzale, A.; Rabatel, A.; Six, D.; Stötter, J.; Strasser, U.; Terzago, S. and Vincent, C. (2018): The European mountain cryosphere: a review of its current state, trends, and future challenges. In: The Cryosphere 12, 759–794. https://doi.org/10.5194/tc-12-759-2018

Benn, D. I. and Evans, D. J. A. (2010): Glaciers and glaciation. London.

Benn, D. I.; Kirkbride, M. P.; Owen, L. A. and Brazier, V. (2005): Glaciated valley systems. In: Evans, D. J. A. (ed.): Glacial landsystems. London, 372–406.

Benson, L.; Madole, R.; Phillips, W.; Landis, G.; Thomas, T. and Kubik, P. (2004): The probable importance of snow and sediment shielding on cosmogenic ages of north-central Colorado Pinedale and pre-Pinedale moraines. In: Quaternary Science Reviews 23, 193–206. https://doi.org/10.1016/j.quascirev.2003.07.002

Blair, R. W. (1994): Moraine and valley wall collapse due to rapid deglaciation in Mount Cook National Park, New Zealand. In: Mountain Research and Development 14, 347–358. https://doi.org/10.2307/3673731

Borchers, B.; Marrero, S.; Balco, G.; Caffee, M.; Goehring, B.; Lifton, N.; Nishiizumi, N.; Phillips, F.; Schaefer, J. and Stone, J. (2016): Geological calibration of spallation production rates in the CRONOS-Earth project. In: Quaternary Geochronology 31, 188–198. https://doi. org/10.1016/j.quageo.2015.01.009

Burrows, C. J. (1973): Studies on some glacial moraines in New Zealand. 2. Ages of moraines of the Mueller, Hooker and Tasman Glaciers. In: New Zealand Journal of Geology and Geophysics 16, 831–855. https://doi.org/10.1080/00288306.1973.10555228

– (1989): Aranuian radiocarbon dates from moraines in the Mount Cook region, New Zealand. In: New Zealand Journal of Geology and Geophysics 32, 205–216. https://doi.org/10.1080/00288306.1989.10427583

– (2005): Julius Haast in the Southern Alps, Christchurch.

Caseldine, C. J.; Turney, C. and Long, A. J. (2010): IPCC and palaeoclimate – an evolving story? In: Journal of Quaternary Science 25, 1–4. https://doi.org/10.1002/jqs.1336

Chinn, T. J. H. (1989): Glaciers of New Zealand - Satellite atlas of glaciers of the World H-2. In: U.S. Geological Survey Professional Paper 1386-H, 25–48.

– (1996): New Zealand glacier responses to climate change of the past century. In: New Zealand Journal of Geology and Geophysics 39, 415–428. https://doi.org/10.1080/00288306.1996.9514723

Chinn, T. J. H.; Winkler, S.; Salinger, M. J. and Haakensen, N. (2005): Recent glacier advances in Norway and New Zealand – a comparison for their glaciological and meteorological causes. In: Geografiska Annaler 87 A, 141–157. https://doi.org/10.1111/j.0435-3676.2005.00249.x

Chinn, T.; Salinger, J.; Fitzharris, B. B. and Willsman, A. (2008): Glaciers and climate. In: Bulletin of the Federal Mountain Clubs of NZ 171, 1–15.

Chinn, T.; Fitzharris, B. B., Willsman, A. and Salinger, N. J. (2012): Annual ice volume changes 1976–2008 for the New Zealand Southern Alps. In: Global and Planetary Change 92-93, 105–118. https://doi.org/10.1016/j.gloplacha.2012.04.002

Corbett, L. B.; Bierman, P. R. and Rood, D. H. (2016): An approach for optimizing in situ cosmogenic ^{10}Be sample preparation. In: Quaternary Geochronology 33, 24–34. https://doi.org/10.1016/j.quageo.2016.02.001

Cox, S. C. and Barrell, D. J. A. (2007): Geology of the Aoraki area - Geological map 1250,000 (15). Lower Hutt.

Dahl, S. O.; Bakke, J.; Lie, Ø. and Nesje, A. (2003): Reconstruction of former glacier equilibrium-line altitudes based on proglacial sites: an evaluation of approaches and selection of sites. In: Quaternary Science Reviews 22, 275–287. https://doi.org/10.1016/S0277-3791(02)00135-X

Davies, T. R. H. (2016): Mountain process geomorphology: conceptual progress in the Southern Alps. In: Shulmeister, J. (ed.): Landscape and Quaternary Environmental Change in New Zealand. Amsterdam, 205–233.

Davis, P. T.; Menounos, B. and Osborn, G. (2009): Holocene and latest Pleistocene alpine glacier fluctuations: a global perspective. In: Quaternary Science Reviews 28, 2021–2033. https://doi.org/10.1016/j.quascirev.2009.05.020

Delunel, R.; Bourlès, D. L.; Van der Beek, P. A.; Schlunegger, F.; Leya, I.; Masarik, J. and Paquet, E. (2014): Snow shielding factors for cosmogenic nuclide dating inferred from long-term neutron detector monitoring. In: Quaternary Geochronology 24, 16–26. https://doi.org/10.1016/j.quageo.2014.07.003

Dortch, J. M.; Owen, L. A. and Caffee, M. W. (2013): Timing and climatic drivers for glaciations across semi-arid western Himalayan-Tibetan orogen. In: Quaternary Science Reviews 78, 188–208. https://doi.org/10.1016/j.quascirev.2013.07.025

Dunai, T. J. (2010): Cosmogenic nuclides. Principles, concepts and applications to earth surface sciences. Cambridge.

Gellatly, A. F. (1982): Holocene glacier activity in Mount Cook National Park, New Zealand. PhD thesis. Canterbury.

– (1985): Historical records of glacier fluctuations in Mt Cook National Park, New Zealand: a century of change. In: Geographical Journal 151, 86–99. https://doi.org/10.2307/633283

Gellatly, A. F.; Chinn, T. J. H. and Röthlisberger, F. (1988): Holocene glacier variations in New Zealand: a review. In: Quaternary Science Reviews 7, 227–242. https://doi.org/10.1016/0277-3791(88)90008-X

Griffiths, G. A. and McSaveney, M. J. (1983): Distribution of mean annual precipitation across some steepland regions of New Zealand. In: New Zealand Journal of Science 26, 197–209.

Grove, J. M. (1979): The glacial history of the Holocene. In: Progress in Physical Geography 3, 1–54. https://doi.org/10.1177/030913337900300101

–. (2004): Little Ice Ages. 2 volumes. London.

Haeberli, W.; Hoelzle, M.; Paul, F. and Zemp, M. (2007): Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps. In: Annals of Glaciology 46, 150–160. https://doi.org/10.3189/172756407782871512

Hambrey, M. J. and Ehrmann, W. (2004): Modification of sediment characteristics during glacial transport in high-alpine catchments: Mount Cook area, New Zealand. In: Boreas 33, 300–318. https://doi.org/10.1080/03009480410001965

Heyman, J.; Stroeven, A. P.; Harbor; J. M. and Caffee, M. W. (2011): Too young or too old: Evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. In: Earth and Planetary Science Letters 302, 71–80. https://doi.org/10.1016/j.epsl.2010.11.040

Heyman, J.; Applegate, P. J.; Blomdin, R.; Gribenski, N.; Habour, J. M. and Stroeven, A. P. (2016): Boulder height - exposure age relationships from a global glacial ^{10}Be compilation. In: Quaternary Geochronology 34, 1–11. https://doi.org/10.1016/j.quageo.2016.03.002

Hoelzle, M.; Chinn, T.; Stumm, D.; Paul, F.; Zemp, M. and Haeberli, W. (2007): The application of glacier inventory data for estimating past climate change effects on mountain glaciers: a comparison between the European Alps and the Southern Alps of New Zealand. In: Global and Planetary Change 56, 69–82. https://doi.org/10.1016/j.gloplacha.2006.07.001

Hogg, A. G.; Hua, Q.; Blackwell, P. G.; Niu, M.; Buck, C. E.; Guilderson, T. P.; Heaton, T. J.; Palmer, J. G.; Reimer, P. J.; Reimer, R. W.; Turney, C. S. M. and Zimmerman, S. R. H. (2013): SHCAL 13 Southern Hemisphere calibration, 0–50,000 years cal BP. In: Radiocarbon 55, 1889–1903. https://doi.org/10.2458/azu_js_rc.55.16783

Huber, U. M.; Reasoner, M. A. and Bugmann, H. (eds.) (2005): Global change and mountain regions – a state of knowledge overview. Dordrecht.

Humlum, O. (1978): Genesis of layered lateral moraines: implications for palaeoclimatology and lichenometry. In: Geografisk Tidsskrift 77, 65–72. https://doi.org/10.1080/00167223.1978.10649094

IPCC (ed.) (2001): Climate change 2001: The physical science basis. Contribution of working group I to the 3rd Assessment report of the Intergovernmental Panel on Climate Change. Cambridge.

– (2007): Climate change 2007: The physical science basis. Contribution of working group I to the 4th Assessment report of the Intergovernmental Panel on Climate Change. Cambridge.

– (2014): Climate change 2013: The physical science basis. Contribution of working group I to the 5th Assessment report of the Intergovernmental Panel on Climate Change. Cambridge.

Kargel, J. S.; Leonard, G. J.; Bishop, M. P.; Kääb, A. and Raup, B. (eds.) (2014): Global land ice measurements from space. Amsterdam.

Kirkbride, M. P. (1995): Processes of transportation. In: Menzies, J. (ed.): Modern glacial environments. Oxford, 261–292.

Kirkbride, M. P. and Winkler, S. (2012): Timescales of climate variability, glacier response, and chronological resolution: issues for correlation of Late Quaternary moraines. In: Quaternary Science Reviews 46, 1–29. https://doi.org/10.1016/j.quascirev.2012.04.002

Korup, O.; Schmidt, J. and McSaveney, M. J. (2005): Regional relief characteristics and denudation pattern of the western Southern Alps, New Zealand. In: Geomorphology 71, 402–423. https://doi.org/10.1016/j.geomorph.2005.04.013

Lawrence, D. B. and Lawrence, E. G. (1965): Glacier studies in New Zealand. In: Mazama 47, 17–27.

Lifton, N.; Sato, T. and Dunai, T. L. (2014): Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. In: Earth and Planetary Science Letters 386, 149–160. https://doi.org/10.1016/j.epsl.2013.10.052

Lowell, T. V.; Schoenenberger, K.; Deddens, J. A.; Denton, G. H.; Smith, C.; Black, J. and Hendy, C. H. (2005): Rhizocarpon calibration curve for the Aoraki/Mount Cook area of New Zealand. In: Journal of Quaternary Science 20, 313–325. https://doi.org/10.1002/jqs.926

Lozán, J. L.; Grassl, H.; Kasang, D.; Nolz, D. and Escher-Vetter, H. (eds.) (2015): Warnsignal Klima: Das Eis der Erde. Hamburg.

Lukas, S.; Graf, A.; Coray, S. and Schlüchter, C. (2012): Genesis, stability and preservation of large lateral moraines of Alpine valley glaciers – towards a unifying theory based on Findelengletscher, Switzerland. In: Quaternary Science Reviews 38, 27–48. https://doi.org/10.1016/j.quascirev.2012.01.022

Marrero, S. M.; Phillips, F. M.; Borchers, B.; Lifton, N.; Aumer, R. and Balco, G. (2016): Cosmogenic nuclide systematics and the CRONUScalc program. In: Quaternary Geochronology 31, 160–187. https://doi.org/10.1016/j.quageo.2015.09.005

Matthews, J. A. (2013): Neoglaciation in Europe. In: Elias, S. A. (ed.): Encyclopedia of Quaternary Sciences. 2nd edition. Rotterdam, 257–268.

Matthews, J. A. and Briffa, K. (2005): The 'Little Ice Age': re-evaluation of an evolving concept. In: Geografiska Annaler 87 A, 17–36. https://doi.org/10.1111/j.0435-3676.2005.00242.x

Matthews, J. A. and Dresser, P-Q. (2008): Holocene glacier variation chronology of the Smørstabbtindan massif, Jotunheimen, southern Norway, and the recognition of century- to millennial-scale European Neoglacial events. In: The Holocene 18, 181–201. https://doi.org/10.1177/0959683607085608

Matthews, J. A.; Shakesby, R. A. and Fabel, D. (2017): Very low inheritance in cosmogenic surface exposure ages of glacial deposits: a field experiment from two Norwegian glacier forelands. In: The Holocene 27, 1406–1414. https://doi.org/10.1177/0959683616687387

Owen, L. A.; Thackray, G.; Anderson, R. S.; Briner, J.; Kaufman, D.; Roe, G.; Pfeffer, W. and Yi,C. (2009): Integrated research on mountain glaciers: Current status, priorities and future prospects. In: Geomorphology 103, 158–171. https://doi.org/10.1016/j.geomorph.2008.04.019

Philips, F. M.; Argento, D. C.; Balco, G.; Caffee, C. W.; Clem, J.; Dunai, T. J.; Finkel, R.; Goehring, B.; Gosse, J. C.; Hudson, A. M.; Jull, A. J. T.; Kelly, M. A.; Kurz, M.; Lal, D.; Lifton, N.; Marrero, S. M; Nishiizumi, K.; Reedy, R. C.; Schaefer, J.; Stone, J. O. H.; Swanson, T. and Zreda, M. G. (2016a): The CRONOS-Earth project: a synthesis. In: Quaternary Geochronology 31: 119–154. https://doi.org/10.1016/j.quageo.2015.09.006

Phillips, F. M.; Argento, D. C.; Bourlès, D. L.; Caffee, C. W.; Dunai, T. J.; Goehring, B.; Gosse, J. C.; Hudson, A. M.; Jull, A. J. T.; Kelly, M. A.; Lifton, N.; Marrero, S. M; Nishiizumi, K.; Reedy, R. C. and Stone, J. O. H. (2016b): Where now? Reflections on future directions for cosmogenic nuclide research from CRONUS projects. In: Quaternary Geochronology 31, 155–159. https://doi.org/10.1016/j.quageo.2015.04.010

Putnam, A. E.; Schaefer, J. M.; Barrell D. J. A.; Vandergoes, M.; Denton, G. M.; Kaplan, M. R.; Finkel, R. C.; Schwartz, R.; Goehring, B. M. and Kelley, A. E. (2010): In situ cosmogenic ^{10}Be production-rate calibration from the Southern Alps, New Zealand. In: Quaternary Geochronology 5, 392–409. https://doi.org/10.1016/j.quageo.2009.12.001

Putnam, A. E.; Schaefer, J. M.; Denton, G. H.; Barrell, D. J. A.; Finkel, R. C.; Schwartz, R.; Chinn, T. J. H. and Doughty, A. M. (2012): Regional climate control of glaciers in New Zealand and Europe during the pre-industrial Holocene. Nature In: Geoscience 5, 627–630. https://doi.org/10.1038/NGEO1548

Reimer, P. J., Reimer, R. W. and Blaauw, M. (2013a): Calibration of the ^{14}C record. In: Elias, S. A. (ed.): Encyclopedia of Quaternary Sciences. 2nd edition, Rotterdam, 345–352.

Reimer, P. J.; Bard, E.; Bayliss, A.; Beck, J. W.; Blackwell, P. G.; Bronk Ramsey, C.; Buck, C. E.; Cheng, H.; Edwards, R. L.; Friedrich, M.; Grootes, P. M.; Guilderson, T. P.; Haflidason, H.; Hajdas, I.; Hatté, C.; Heaton, T. J.; Hoffmann, D. L.; Hogg, A. G.; Hughen, K. A.; Kaiser, K. F.; Kromer, B.; Manning, S. W.; Niu, M.; Reimer, R. W.; Richards, D. A.; Scott, .M.; Southon. J. R.; Staff, R. A.; Turney, C. S. M. and Van der Plicht, J. (2013b): IntCal 13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. In: Radiocarbon 55, 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947

Reznichenko, N. V.; Davies, T. R,; Shulmeister, J. P. and Larsen, S. H. (2012a): A new technique for identifying rock avalanche-sourced sediment in moraines and some palaeoclimatic implications. In: Geology 40, 319–322. https://doi.org/10.1130/G32684.1

Rezninchenko, N. V.; Davies, T. R.; Shulmeister, J. P. and Winkler, S. (2012b): Influence of rock avalanches upon the formation of moraines and their subsequent palaeoclimatic interpretation: a critical appraisal. In: Zeitschrift für Geomorphologie N.F. 56 Supplementary Issues 4, 37–54. https://doi.org/10.1127/0372-8854/2012/S-00079

Rezninchenko, N. V.; Davies, T. R. H. and Winkler, S. (2016): Revised palaeoclimatic significance of Mueller Glacier moraines, Southern Alps, New Zealand. In: Earth Surface Processes and Landforms 41, 196–207. https://doi.org/10.1002/esp.3848

Röthlisberger, F. (1986): 10.000 Jahre Gletschergeschichte der Erde. Aargau.

Röthlisberger, F. and Schneebeli, W. (1979): Genesis of lateral moraine complexes, demonstrated by fossil soils and trunks: indicators of postglacial climatic fluctuations. In: Schlüchter, C. (ed): Moraines and varves. Rotterdam, 387–419.

Schaefer, J. M.; Denton, G. H.; Kaplan, M.; Putnam, A.; Finkel, R. C.; Barrell, D. J. A.; Andersen, B. G.; Schwartz, R.; McIntosh, A.; Chinn, T. and Schlüchter, C. (2009): High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature. In: Science 324, 622–625. https://doi.org/10.1126/science.1169312

Schildgen, T. F.; Phillips, W. M. and Purves, R. S. (2005): Simulation of snow shielding corrections for cosmogenic nuclide surface exposure dating. In: Geomorphology 64, 67–85. https://doi.org/10.1016/j.geomorph.2004.05.003

Schimmelpfennig, I.; Schaefer, J. M.; Akçar, N.; Koffman, T.; Ivy-Ochs, S.; Schwarz, R.; Finkel, R. C.; Zimmerman, S. and Schlüchter, C. (2014): A chronology of Holocene and Little Ice Age glacier culminations of the Steingletscher, Central Alps, Switzerland, based on high-sensitivity beryllium-10 moraine dating. In: Earth and Planetary Science Letters 393, 220–230. https://doi.org/10.1016/j.epsl.2014.02.046

Shulmeister, J., Davies, T. R., Evans, D. J. A., Hyatt, O. M. and Tovar, D. S. (2009): Catastrophic landslides, glacier behaviour and moraine formation - A view from an active plate margin. In: Quaternary Science Reviews 28, 1085–1096. https://doi.org/10.1016/j.quascirev.2008.11.015

Slaymaker, O. and Embleton-Hamann, C. (2018): Advances in global mountain geomorphology. In: Geoorphology 308, 230–264. https://doi.org/10.1016/j.geomorph.2018.02.016

Slaymaker, O. and Kelly, R. E. J. (2007): The cryosphere and global environmental change. Oxford.

Solomina, O. N.; Bradley, R. S.; Hodgson, D. A.; Ivy-Ochs, S.; Jomelli, V.; Mackintosh, A. N.; Nesje, A.; Owen, L. A.; Wanner, H.; Wiles, G. C. and Young, N. E. (2015): Holocene glacier fluctuations. In: Quaternary Science Reviews 111, 9–34. https://doi.org/10.1016/j.quascirev.2014.11.018

Solomina,O. N.; Bradley, R. S.; Jomello, V.; Geirsdottir, A.; Kaufman, D. S.; Koch, J.; McKay, N. P.; Masiokas, M., Miller, G.; Nesje, A.; Nicolussi, K.; Owen, L. A.; Putnam A. E. Wanner, H.; Wiles, G. C. and Yang, B. (2016): Glacier fluctuations during the past 2000 years. In: Quaternary Science Reviews 149, 61–90. https://doi.org/10.1016/j.quascirev.2016.04.008

Tedesco, M. (ed.) (2015): Remote sensing of the cryosphere. Chichester.

von Blankenburg, F. and Willenbring, J. K. (eds.) (2014): Cosmogenic nuclides. Elements 10 (5), Richland WA.

Wanner, H.; Beer, J.; Bütikofer, J.; Crowley, T. J.; Cubasch, U.; Flückinger, J.; Goosse, H.; Grosjean, M.; Joos, F.; Kaplan, J. O.; Küttel, M.; Müller, S. A.; Prentice, C.; Solomina, O.; Stocker, T. F.; Tarasov, P.; Wagner, M.

and Widmann, M. (2008): Mid- to Late Holocene climate change: an overview. In: Quaternary Science Reviews 27, 1791–1828. https://doi.org/10.1016/j.quascirev.2008.06.013

WGMS (World Glacier Monitoring Service) (2008): Global glacier changes: facts and figures. Zürich.

Winkler, S. (2000): The 'Little Ice Age' in the Southern Alps, New Zealand - preliminary results at Mueller Glacier. In: The Holocene 10, 643–647. https://doi.org/10.1191/095968300666087656

– (2001): Untersuchungen zur Klima- und Morphodynamik in skandinavischen Gebirgsregionen während des Holozän - ein Vergleich ihrer Wechselwirkungen und Prozeßsysteme im überregionalen Kontext kaltgemäßigter maritimer Gebirgsregionen. Habilitation thesis. Trier.

– (2005): The 'Schmidt hammer' as a relative-age dating technique: potential and limitations of its application on Holocene moraines in Mt Cook National Park, Southern Alps, New Zealand. In: New Zealand Journal of Geology and Geophysics 48, 105–116. https://doi.org/10.1080/00288306.2005.9515102

– (2009): Gletscher und ihre Landschaften. Darmstadt.

– (2014): Investigation of late-Holocene moraines in the western Southern Alps, New Zealand, applying Schmidt-hammer exposure-age dating (SHD). In: The Holocene 24, 48–66. https://doi.org/10.1177/0959683613512169

– (2015a): Observations of paraglacial processes on glacier forelands of Aoraki/Mount Cook National Park, Southern Alps, New Zealand. In: Geophysical Research Abstracts 17, EGU2015-1492. https://meetingorganizer.copernicus.org/EGU2015/EGU2015-1492.pdf

– (2015b): Die gegenwärtige Situation der Gletscher auf Neuseeland. In: Lozán, J. L.; Grassl, H.; Kasang, D.; Nolz, D. and Escher-Vetter, H. (eds.): Warnsignal Klima: Das Eis der Erde. Hamburg, 123–129.

Winkler, S. and Hagedorn, H. (1999): Lateralmoränen - Morphologie, Genese und Beziehung zu Gletscherstandsschwankungen (Beispiele aus Ostalpen und West-/Zentralnorwegen). In: Zeitschrift für Geomorphologie N.F. Supplement Band 113, 69–84.

Winkler, S. and Matthews, J. A. (2010a): Holocene glacier chronologies: Are 'high-resolution' global and inter-hemispheric comparisons possible? In: The Holocene 20, 1137–1147. https://doi.org/10.1177/0959683610369511

– (2010b): Observations on terminal moraine-ridge formation during recent advances of southern Norwegian glaciers. In: Geomorphology 116, 87–106. https://doi.org/10.1016/j.geomorph.2009.10.011

Winkler, S. and Nesje, A. (1999): Moraine formation at an advancing temperate glacier, Brigsdalsbreen, western Norway. In: Geografiska Annaler 81 A, 17–30. https://doi.org/10.1111/j.0435-3676.1999.00046.x

Winkler, S.; Chinn, T.; Gärtner-Roer, I.; Nussbaumer, S. U.; Zemp, M. and Zumbühl, H. J. (2010): An introduction to mountain glaciers as climate indicators with spatial and temporal diversity. In: Erdkunde 64, 97–118. https://doi.org/10.3112/erdkunde2010.02.01

Wittmeier, H. E.; Bakke, J.; Vasskog, K. and Trachsel, M. (2015): Reconstructing Holocene glacial activity at Landfjordjøkulen, Arctic Norway, using multi-proxy fingerprinting of distal glacier-fed lake sediments. In: Quaternary Science Reviews 114, 78–99. https://doi.org/10.1016/j.quascirev.2015.02.007

Zemp, M.; Hoelzle, M. and Haeberli, W. (2009): Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. In: Annals of Glaciology 50, 101–111. https://doi.org/10.3189/172756409787769591

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