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Glacial trimlines to identify former ice margins and subglacial thermal boundaries: a review and classification scheme for trimline expression

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Abstract

Reconstructions of former ice sheets and glaciers provide important palaeoglaciological information about their behaviour in response to climate changes. Glacial trimlines record both the margin positions and palaeo ice thickness, enabling the production of empirically constrained 3-Dimensional reconstructions. However, the literature review into the characteristics, interpretation, and use of glacial trimlines here presented shows that these features have been under-utilised and are poorly described in the existing literature, with a confusing terminology currently in use. A new classification scheme and terminology for trimline identification and interpretation is developed to better facilitate further research into these common features of glacierised and formerly glaciated landscapes.

Keywords: trimline; trim-line; trim line; ice margin; geomorphology; glacial reconstruction

1. Introduction

The former extent of glaciers, ice caps and ice sheets can often be reconstructed by plotting evidence of their margin positions by using moraines, ice-marginal fans or the limit of glacial deposits. Such evidence defines the former spatial footprint of the ice mass saying little about its thickness or vertical extent. On mountain flanks however, it is sometimes possible to define the former vertical extent of ice cover as marked by linear traces across hillslopes and which have been termed glacial trimlines. In its simplest idealisation, glacier flow eroded away vegetated hillslopes 'trimming' them such that a clear limit of the glacier is left behind to be observed once the ice receded (Figure 1). Due to their ability to record both the horizontal and vertical dimensions of palaeo ice masses, glacial trimlines are important for the production of 3-dimensional (3D) reconstructions (Ballantyne 2010). This permits calculation of the ice volume and computation of the changes in ice thickness and volume between different glacial events or time periods and comparison with climate records. Additionally, 3D reconstructions are useful for testing and refining numerical modelling of ice masses, which are then used to better understand modern ice masses and predict their responses to on-going climate changes.

Despite the usefulness of glacial trimlines they have mostly been reported on a case-by-case basis, with little systematic exploration of their formation, expression and morphology, and their preservation and distribution. Here we review the literature surrounding glacial trimlines and identify areas of conflict as well as under-researched aspects of these features. A discussion of the origins, development and usage of trimline terminology in the literature identifies a confusing and ambiguous set of terms currently in use. We therefore propose a new definition for 'glacial trimline', as well as a suggested classification scheme to assist with their identification and usage. The applications of glacial trimlines in reconstructions of Quaternary and more recent historic glacial events (e.g. the Little Ice Age) will also be explored and the distribution of trimline studies globally summarised. The unexplored potential of trimlines will be highlighted.

2. What is a trimline?

This question is more complex than it may first appear due to the range of different glaciogenic features that have been termed 'trimlines', or that overlap with glacial trimlines in terms of expression or usage. For example, differences in the vegetation density on glacierised valley sides have been termed 'trimlines' (e.g. Wolken *et al.*

2005; Harrison *et al.* 2007; Kelley *et al.* 2012). Similarly, distinctions between zones of glacial erosion compared to adjacent areas of periglacial weathering in settings of Quaternary glaciation have also been called 'trimlines' (e.g. McCarroll *et al.* 1995; Ballantyne *et al.* 1998b; Rae *et al.* 2004; McCarroll 2016). These breaks or contrasts in surface characteristics may have formed in different ways but both arise from some sort of 'trimming', can be interpreted as former ice margin positions, and may record ice thickness at the time of their formation. These types of features are what has been traditionally thought of as glacial trimlines and are most likely what comes to the majority of researchers' minds when they hear the term.

However, it is also possible to view 'trimlines' as a transition area between two slope zones with differing characteristics, rather than as a single linear feature. In these cases, the term 'trimzone' may be used in place of or as well as 'trimline' (Figure 2; e.g. Csatho *et al.* 2005; Forman *et al.* 2007; Csatho *et al.* 2008). Additionally, the term 'trimline moraines' has been used for frontal features (Ó Cofaigh *et al.* 2003), in contrast to the more usual usage that trimlines are features of the lateral ice margin.

It is rare to find an explicit definition of 'trimline' in the literature. The majority of papers discussing glacial trimlines simply use the term without either giving a definition or referring to a previous definition. The meaning of the term 'trimline' can vary, creating ambiguity and potential confusion.

2.1 Trimline manifestations

Our review of the literature suggests that glacial trimlines can be expressed by a variety of means, which are not mutually exclusive within a single trimline or group of trimlines. Some terms previously employed in the literature have included description of trimline expression, such as 'vegetation trimline' (e.g. Figure 1; Wolken *et al.* 2005; Harrison *et al.* 2007; Kelley *et al.* 2012) and 'weathering limit' (e.g. Ballantyne and Harris 1994; Rae *et al.* 2004; Evans *et al.* 2005; Boulton and Hagdorn 2006; Ballantyne *et al.* 2009). However, many manifestations of glacial trimlines do not have explicit terms and individual trimline features are rarely described in detail, making it difficult to identify the full range of possible trimline manifestations or to compare the expression of trimlines in different study areas. This lack of a clear understanding of the ways in which trimlines can be expressed adds to the uncertainty surrounding the clear identification of what constitutes a glacial trimline.

2.2 Quaternary and historic trimlines

For the purpose of this literature review, trimlines will be referred to by age as either Quaternary or historic. Quaternary trimlines are associated with the glaciations of the Quaternary geological period prior to the Little Ice Age (LIA; ca. 1300 to 1850 AD), i.e. these are trimlines associated with glacial events for which we have no written historical record. Conversely, historic trimlines were formed more recently, particularly glacial retreat from the LIA readvance and in response to the on-going modern climate change. This distinction between Quaternary and historic trimlines is made because of significant differences in the methods used to research trimlines of different ages. Additionally, there may be differences in the expression of historic and Quaternary trimlines as well as differences in the applications of historic trimline research compared to Quaternary.

2.3 Trimline terminologies

Efforts to identify the origin of the term ‘trimline’ have proved inconclusive and no coining definition has been discovered. However, the term ‘trimline’ appears to have been an established part of the research lexicon by the start of the 1950s (e.g. Lawrence 1950a/b; Mathews 1951; Heusser *et al.* 1954). Prior to the 1950s, trimline features were being utilised in palaeoglaciological reconstructions but without any specific term applied to describe them (e.g. in Scotland by J. Geikie 1873; 1878; and in Wales by Fearnsides 1905). James Geikie (1873; 1878) provides an early example, possibly the first, of the use of trimline features for reconstructions on Harris and South Uist in Scotland. Geikie describes clear contrasts between glacial erosion in lowland areas compared with summit-top frost weathering and used the altitude of these contrasts to determine the ice thickness of the regional glaciation. A typical example of Geikie’s description of the weathering contrasts, in this case on the mountain Hecla on the island of South Uist, makes it clear that these features would now be termed ‘trimlines’.

“Nothing can be more distinct than the line of demarcation between its sharp, jagged, peaked summit and its rounded, softly outlined shoulders, with their *moutonnée* surface.”

(J. Geikie 1878, pp.851)

The first identifiable usage of the term ‘trimline’ appears in North American studies of vegetation trimlines in the early 1950s (Lawrence 1950a/b; Mathews 1951; Heusser *et al.* 1954). Lawrence provides an early definition, describing ‘forest trimlines’ as “the line representing the maximum position attained by the ice front, where the forest was sheared off [trimmed] by the ice” (1950a, pp.243). During the 1950s the term ‘trimline’ was quickly adopted in other areas, such as Patagonia (Nicols and Miller 1951), and went on to become the dominant term for these glacial features over the following decades (Table 1).

The early North American studies used dendrochronology to date changes in vegetation cover and reconstruct former ice limits, a process that was originally developed to identify palaeo nunataks and test the 'glacial refugia' hypothesis (Ives 1974). In Britain and Scandinavia, trimline research took a slightly different path, focused more on identifying weathering contrasts and the limits of glacial erosion (McCarroll *et al.* 1995; Kleman and Stroeven 1997; Ballantyne *et al.* 1997; Ballantyne *et al.* 1998b; Lamb and Ballantyne 1998; Stone *et al.* 1998; Hättestrand and Stroeven 2002; Stroeven *et al.* 2002; Rae *et al.* 2004; Evans *et al.* 2005; Nesje *et al.* 2007; Goehring *et al.* 2008; Ballantyne *et al.* 2009). The age of most recent glaciation in these areas meant that there is lack of vegetation trimlines, so the identification of palaeo nunataks used the distribution of streamlined glacial landforms compared to evidence of periglacial weathering, particularly tors (e.g. Linton 1949; Linton 1950; Dahl 1955; Linton 1955). The identification of thick periglacial deposits on mountain summits, particularly in Scotland (Ballantyne 1998), was also suggested to be diagnostic of palaeo nunataks. This led to the emergence of the term 'periglacial trimline' in British trimlines research and the use of these features to reconstruct palaeo ice thickness, after Geikie's early example (Ballantyne and Harris 1994).

In Scandinavia, trimline interpretation was influenced by Sugden's work on identifying landscapes of differing glacial erosion and linking these to palaeo thermal regime (summarised in Sugden and John 1976). Researchers applied these ideas in Scandinavia (e.g. Kaitanen, 1969; Kleman and Borgström 1990; Kleman and Stroeven 1997) to identify areas of glacial erosion, indicating warm-based ice, and places where pre-glacial landscapes were preserved under cold-based ice. Recognition of trimlines within the palimpsest glacial landscapes of Scandinavia and new understandings of the role of thermal regime in producing these features led to the suggestion that trimlines are not always ice marginal but can sometimes indicate a boundary between areas of warm- and cold-based ice beneath a former ice sheet. This discovery has led to the development of a range of terms to distinguish the two possible trimline origins, such as 'ice marginal trimline' (e.g. Nesje *et al.* 2007) and 'thermal trimline' (e.g. Zasadni and Kłapyta 2014).

Previous trimline research has also discussed 'weathering zones' (e.g. Ives 1976; Ives *et al.* 1976; Ives 1978; Ballantyne *et al.* 1998a; Clark, P.U. *et al.* 2003; Sugden *et al.* 2005; Goehring *et al.* 2008) and 'erosional zones' (e.g. Hättestrand and Stroeven 2002;

Nesje *et al.* 2007; Fu *et al.* 2013). It is notable that, although there are several exceptions (e.g. Ballantyne *et al.* 1998a in Britain; Sugden *et al.* 2005 in Antarctica; Fu *et al.* 2013 in Tibet), there appears to be a preference for using zonal terminology in North American (e.g. Ives 1976; Ives *et al.* 1976; Ives 1978; Clark, P.U. *et al.* 2003) and Scandinavian trimline research (e.g. Hättestrand and Stroeven 2002; Nesje *et al.* 2007; Goehring *et al.* 2008). Outside of these areas, trimlines are more commonly referred to in a linear sense as lines, limits, boundaries or similar (Table 1; Figure 3). The use of different terminology in different places is a further confusing factor that complicates the discussion of glacial trimlines in the existing literature.

Terms like 'periglacial trimline', 'erosional trimline' and 'thermal trimline' indicate a suggested interpretation, rather than solely describing the trimline expression. Similar interpretative terms, such as 'glacier limit' (Sissons 1974) and 'subglacial zone' (Hättestrand and Stroeven 2002), also suggest either an ice marginal or subglacial interpretation for the formation of the trimline feature. Other terms, such as 'ice sheet trimline' (Ballantyne *et al.* 1998a) or 'palaeo-trimline' (Hubbard *et al.* 2009), suggest that the trimline is linked to a particular style of glaciation or glacial period. Still other terms indicate an interpretation of the significance of a trimline feature within a given study area. For example, Nesje *et al.* (2007) use the term 'regional trimline' to describe the average trimline altitude across their study area. Over time there has been an increasing diversity of trimline expressions that have been identified and discussed, and the use of differing terms for broadly similar features can have the effect of diluting the literature by causing researchers to miss papers that have used terms from the other group.

In summary, a wide range of terms are in use to describe trimline features and these are often not mutually exclusive and may be used interchangeably, creating ambiguity. Additionally, there is a lack of standardisation within trimline terminologies, with different terms or groups of terms used at different times and in different places (Figure 3). There are several useful terms that describe a particular way in which trimlines can be expressed, such as 'vegetation trimline', but many forms of trimline expression do not have an appropriate descriptive term. Many of the most common terms for glacial trimlines imply a degree of interpretation, rather than remaining solely descriptive. This fact is often not made clear and leads to confusing and sometimes conflicting usage of the established terminology. We suggest that trimline research would be improved by the application of a simplified and standardised terminology that has specific descriptive terms for all observable means of trimline expression and a clear distinction between descriptive and interpretative terms.

3. Approaches to trimline research

Early research mapped and identified trimline features via extensive fieldwork (e.g. Geikie 1873; 1878). However, it was immediately clear that trimlines are often more visible from a distance, a fact that Geikie (1878) noted in his description of trimlines in the Hebrides Islands of Scotland. Despite these observations, it was not until the 1980s that trimlines were mapped from secondary data. The key paper that defined a method for identifying and mapping trimlines from aerial imagery was Thorp (1981), who used glacial trimlines in his reconstruction of an ice cap on Rannoch Moor in Scotland. Thorp's method describes best practice for using a combination of aerial photographs and field mapping to identify the trimlines separating areas of glacial erosion in the valleys from areas of periglacial weathering on mountain summits (Figure 4). The 1981 paper set the precedent for mapping trimlines using a combination of aerial imagery and fieldwork observations and also established a method for linking trimlines across different mountains, which was further developed by Thorp (1986, 1987).

Subsequently, several authors have applied Thorp's methods to other areas in Britain and Ireland and of these the work of Ballantyne has been particularly significant because of both the number of papers utilising trimlines and due to his application of cosmogenic nuclide dating to trimline features (summarised in Ballantyne 2010 and MacCarroll 2016). Brook et al. (1996) were the first to use cosmogenic nuclides to date weathering limits, using this information to reconstruct Younger Dryas ice cover in Norway. The work of Brook et al. (1996) motivated Stone et al. (1998) to apply the cosmogenic nuclide method to test trimline interpretations on the Isle of Skye and in the north-western Scottish Highlands. Arising from further cosmogonic exposure age estimates a really major change in trimline investigations occurred when it was finally demonstrated that trimlines do not necessarily record ice margin elevations but that they can also arise from subglacial boundaries between erosive warm-based ice and non-erosive cold-based ice at higher elevations (Figure 5). Such a shift in interpretation drastically changes a reconstruction of ice sheet thickness from relatively thin ice with exposed nunataks, to thicker ice with mountain summits covered. Such cosmogenic dating became pivotal in the interpretation of trimlines and was able to identify examples of both ice marginal and thermal trimlines (e.g. Ballantyne et al. 1998b; Stone and

Ballantyne 2006; Ballantyne et al. 2009; Ballantyne et al. 2011; McCormack et al. 2011; Fabel et al. 2012; Glasser et al. 2012; Ballantyne and Stone 2015).

Lately, methods of trimline mapping have been developed beyond the aerial method of Thorp (1981; 1986) through the use of satellite imagery. Knight et al. (1987) showed that a multispectral classification of satellite imagery could be used to identify and map the changes in vegetation that mark the Little Ice Age (LIA) trimzone in Greenland. Improvements in the coverage, resolution and availability of satellite imagery have enabled much larger-scale trimline mapping investigations such as Glasser et al.'s (2005; 2008) reconstruction of the glacial history of Patagonia using data from the satellites Landsat 7 and ASTER. These larger-scale reconstructions are particularly significant for validating ice sheet models.

Improvements in Geographic Information Science (GIS) have also led to progress in trimline research by enabling more advanced processing and increasing the speed of trimline mapping across large areas. An example is the work of Kelly et al. (2004), who reconstructed the Last Glacial Maximum (LGM) accumulation area ice surface in the Swiss Alps. They mapped trimlines in the field and compared them to a digitisation of an existing reconstruction, using the trimlines to refine the accumulation area geometry. This method was only possible using GIS software to combine the previous reconstruction and the new accumulation area trimline evidence into a single ice surface reconstruction. It is noteworthy that Kelly et al. had to assume that all the maximum glaciation landforms and trimlines in their study area were synchronous. This is an issue common to all regional trimline studies. At present there is no certain way to determining synchroneity between trimlines, particularly in different valleys or on different massifs. Wider application of cosmogenic nuclide dating may help to combat this problem but the large error ranges involved in this dating method can still prevent definitive establishment of synchroneity or lack thereof.

Improvements in satellite imagery and GIS capabilities enabled Csatho and colleagues to produce a semi-automated method for mapping vegetation trimlines over large areas (Csatho et al. 2005; van der Veen and Csatho 2005). Their method used multispectral imagery from the Landsat 7 satellite to classify the land surface from which they were able to map the LIA trimzone and associated trimline in Jakobshavn Isfjord, west Greenland. Csatho et al. (2008) expanded on this initial study, utilising the same method but comparing the trimline altitude with recorded ice margin positions to determine rates of ice loss in the study area since the LIA. Building on the work of Csatho et al., Kjeldsen et al. (2015) produced the first, and so far only, empirically based 3D reconstruction of the entire Greenland Ice Sheet during the LIA. Their method involved using vertical stereo photogrammetric aerial imagery to map LIA trimlines in 3D and to compare them to the ice margin position at the time of the photographic survey (1978-1987 AD). By extrapolating from the trimlines, they were able to compute the extent and spatial distribution of ice surface elevation and volume changes for the entire ice sheet between the peak of the LIA (assumed to be 1900 AD) and the aerial survey in 1978-1987 AD.

Whilst many of the approaches to trimline research are the same between Quaternary and historic trimlines, there can be significant differences in the application of research methods, as well as differences in the analysis and interpretation of these features (Figure 6). In general, Quaternary trimline research places more emphasis on field observations and analyses, compared to the greater significance of remotely sensed data in historical studies. Many Quaternary trimline studies have quantified the contrast in weathering across a trimline using Schmidt hammer measurements, bedrock joint depth analysis and by studying the soil composition above and below the trimline (e.g. McCarroll et al. 1995; Rae et al. 2004; Nesje et al. 2007; see summary of these methods in McCarroll 2016). The use of X-ray diffraction clay-fraction mineralogy is particularly common in Quaternary settings, especially when trying to determine if a trimline is of ice marginal or thermal origin (e.g. McCarroll et al. 1995; Dahl, S.-O. et al. 1996; Ballantyne 1997; Lamb and Ballantyne 1998; Ballantyne et al. 1998b; Ballantyne 1998; McCarroll and Ballantyne 2000; Ballantyne and Hallam 2001; Rae et al. 2004; Ballantyne et al. 2006; Ballantyne et al. 2007; Nesje et al. 2007; Ballantyne et al. 2008; Ballantyne et al. 2011).

In historic settings the modern ice surface is often present, potentially acting as a guide for reconstructing the morphology of the previous ice surface, and it is usually clear whether a trimline is ice marginal or thermal in origin (Figure 6). Research into historic trimlines can also make use of additional data sources that are not available for Quaternary settings. For example, repeat aerial surveys and high-resolution satellite imagery of some glacierised areas can allow comparison of the modern ice margin to a series of trimlines and other recorded ice margin positions, which enables rates of down-wasting to be computed (e.g. Harrison et al. 2007; Csatho et al. 2008; Glasser et al. 2011).

Historic glacial limits are often recorded in paintings, sketches, documents and photographs. These secondary data can provide additional ice margin positions and can help to date trimlines and establish synchroneity between trimlines and other glacial features. Validation studies have found these secondary data to be generally accurate representations of the former ice extent (e.g. in the Alps by Nussbaumer et al. 2007 and Zumbühl et al. 2008). Therefore, historic reconstructions in well-documented areas can be produced with higher confidence and with much more detail than is possible for Quaternary reconstructions, even when the trimline record is similarly preserved. However, the availability of secondary data may be contributing to the tight spatial focus of historic trimlines research in well-documented areas (Figure 7).

It appears more common to find multiple trimlines associated with the same ice margin in historic settings compared to Quaternary. This is likely to be a function of the preservation potential of trimline features. For example, Forman et al. (2007) identified a clear LIA vegetation trimline associated with the ice margin in the Kangerlussuaq area of west Greenland but they also noticed several subtler changes in vegetation cover within the LIA trimzone. These features may well be trimlines linked to standstills during the post-LIA retreat of the ice margin. These subtler trimlines probably do not have long-term preservation potential and may well not survive in Quaternary settings.

4. How and where have trimlines been used?

Quaternary trimline research has been primarily focused in the British Isles, Scandinavia and in North America (Figure 7a; Table 2). However, Quaternary trimlines have also been identified and studied in other locations (e.g. in the Balkans by Hughes *et al*. 2006; Hughes *et al*. 2010; Ribolini *et al*. 2017; and Temovski *et al*. 2018; Figure 7d). The temporal focus of Quaternary trimline research has been on the deglaciation from the Last Glacial Maximum (LGM c. 21 ka BP) (e.g. Ives 1976; Ballantyne 1997; Florineth and Schluchter 1998; Kaplan *et al.* 2001; Kelly *et al.* 2004; Sugden *et al.* 2005; Ballantyne *et al.* 2006; Hubbard *et al.* 2006; Stone and Ballantyne 2006; Nesje *et al.* 2007; Glasser *et al.* 2008). In North America and in Europe there has also been significant interest in reconstructing Younger Dryas (c. 13 ka - 11 ka BP) ice limits from trimlines (e.g. Thorp 1981; Thorp 1986; Bennet 1994; Ballantyne 2007). This focus on the LGM and the Younger Dryas is common to all empirical Quaternary reconstructions because the landform record is better preserved for these more recent glacial events compared to more ancient Quaternary glaciations. However, in some locations older trimlines are preserved and have been used to reconstruct glacial fluctuations over much longer time periods. Older trimlines have primarily been found in areas of rugged terrain in West Antarctica, such as the Ohio Range, where the glaciations of the last 200 ka have been dated from trimlines and erratics (Ackert *et al.* 2011), and in the Ellsworth

Mountains, where a glacial trimline has been dated to at least 2 million years ago and could be as old as c. 14 million years (Sugden *et al.* 2017).

Research into historic trimlines has been focused in the Americas and in Greenland (Figure 7b; Table 2) on reconstructing the extent of the Little Ice Age readvance (LIA 1700-1930 AD) (e.g. McKinzey *et al.* 2004; Glasser *et al.* 2005; Wolken *et al.* 2005; Forman *et al.* 2007; Csatho *et al.* 2008; Glasser *et al.* 2011). Surprisingly, little research has considered the very recent trimlines exposed by the rapid glacial retreat recorded over the past 100 years, although it is possible to observe these features in recent and historic photographs of glaciers as well as in the field (Rootes 2018).

Thus far trimline research has focused predominantly on vegetation trimlines in historic settings and on contrasts in glacial erosion compared to periglacial weathering in Quaternary settings. This narrow focus does not include the full range of possible modes of trimline expression, many of which have received little to no attention (see later).

Given the focus on a narrow range of places, modes of trimline expression, and time periods, both Quaternary and historic trimlines are probably being under-utilised at present. The recent discovery of possible glacial trimlines on Mars (Gourronc *et al.* 2014) also raises the possibility of expanding the use of these landforms into extra-terrestrial settings. Exploration of a wider range of modes of trimline expression may also prove fruitful, as could further consideration of associated landforms, such as lateral moraines, which have not generally come under the 'trimline' umbrella but that can be used in similar ways and are often found alongside other glacial trimline expressions (e.g. Ives 1976; Clark, P.U. *et al.* 2003; Glasser *et al.* 2005; 2008; Hormes *et al.* 2008; Carrivick et al. 2019). These features may benefit from consideration as a type of glacial trimline, alongside other trimline features.

For all temporal periods and all geographic locations, the ability to produce 3D reconstructions using trimlines has been of particular significance. Estimates of palaeo ice thickness, derived from trimlines, allow ice volume change to be computed and have enabled the quantification of the sea level contribution of ice loss (e.g. Glasser *et al.* 2011; Kjeldsen *et al.* 2015; Edwards *et al.* 2017). Trimline studies are also utilised to test the outputs of numerical ice sheet models, a process used to validate and improve the models and hence predictions of future ice sheet behaviour (e.g. Dahl, S.-O. *et al.* 1996; Lamb and Ballantyne 1998; McCarroll and Ballantyne 2000; Ballantyne and Hallam 2001; Hubbard *et al.* 2006; Ackert *et al.* 2007).

The 3D reconstructions produced from Quaternary trimlines can be used to reconstruct palaeoclimate. Trimline distribution over large areas can reveal details of the surface morphology of the palaeo ice mass that may indicate particular palaeo wind patterns and precipitation gradients (Glasser *et al.* 2008). Palaeo equilibrium line altitude (ELA) can also be derived from 3D ice surface reconstructions. The ELA is roughly equivalent to the snow line altitude and, as well as being a climate proxy in itself, is also useful for calculating palaeo mass balance and for studying the impact of glaciers on long-term landscape evolution, due to the links between ELA position and patterns of glacial erosion (Ballantyne 2007). Trimlines are particularly important for ELA reconstructions because they record ice thickness and are one of the only ice marginal features that can be found in the accumulation area, above the ELA (Thorp 1981; Kelly *et al.* 2004). An example of the use of trimlines in ELA reconstruction is van der Beek and Bourbon (2008), who used trimlines to reconstruct ice thickness and palaeo ELA in the French Alps in order to quantify the impact of glacial erosion on the topography of the region.

Reconstructions produced from Quaternary trimlines can also be used to determine ice thickness and volume changes (e.g. Figure 6). The use of ice marginal trimlines to determine ice thickness has been termed the 'dipstick' method, in reference to engine oil dipsticks in cars (Mackintosh *et al.* 2007). For example, Mackintosh *et al.* (2007) looked for the upper limits of erratic distribution, which could be considered a type of trimline, on a transect of mountains in Mac. Robertson Land, East Antarctica. From the altitude of the erratics they were able to determine the LGM ice thickness and, by comparing the trimlines to the modern ice surface, they were able to conclude that there has been little thinning in the study area since the LGM. Research of this 'dipstick' style in Antarctica is particularly significant because of the longer landform record preserved there, compared to that typically found in mid-latitude settings. This allows for the production of longer-term reconstructions, which can be compared to ice core climate records and to measurements of post-glacial isostatic adjustment (e.g. Armienti and Baroni 1999; Ackert *et al.* 2007; Ackert *et al.* 2011; White and Fink 2014). These long-term linked ice thickness and climate studies are particularly important for testing and empirically constraining ice sheet models (e.g. Ackert *et al.* 2011).

In addition to ice marginal trimlines, research into the Quaternary trimlines of Scandinavia and the BIIS has identified examples of palaeo thermal boundaries, for example in the Caithness area of northern Scotland (Ballantyne and Hall 2008). Thermal trimlines such as these are less applicable for reconstructing ice volume loss but instead provide useful information about the distribution of warm-based and cold-based ice at the base of the ice sheet (Goodfellow 2007; Kleman and Glasser 2007; Sugden *et al.* 2005; Baroni *et al.* 2008; in Tibet: Fu *et al.* 2013). This information can also be used to test numerical ice sheet models and can shed light on patterns of glacial erosion and ice flow pathways (Boulton and Hagdorn 2006).

As well as testing numerical models, Quaternary trimline reconstructions have also been used to validate satellite measurements. An example is the work of White and Fink (2014), who used cosmogenically dated trimlines in East Antarctica to reconstruct ice thickness and compared their results to the gravimetric measurements of the GRACE satellites. This comparison allowed them to validate the satellite data and to improve the outputs of isostatic adjustment models, which use the satellite's measurements as input data. Without the ice thickness information recorded in Quaternary trimlines, it would not be possible to carry out this kind of empirical validation of GRACE isostasy measurements.

Historic 3D reconstructions can be produced to a higher resolution, both spatially and temporally, than is possible for Quaternary reconstructions. The higher accuracy and resolution of historic reconstructions mean that they may be used with greater confidence for the same applications as Quaternary reconstructions. This includes testing numerical ice sheet models; although historic reconstructions may not cover a long enough time period to test models of lower temporal resolution or to constrain longer-term experiments.

Where multiple historic ice margin positions are dated, from a series of glacial trimlines or from documentary evidence, it is possible to calculate rates of surface-lowering between ice margin positions (e.g. Figure 6; Kohler *et al.* 2007). The extent and rate of surface-lowering can be compared with climate records to infer the response rate and retreat style of the glacier (e.g. Navarro *et al.* 2005; Kohler *et al.* 2007). Estimates of glacier response times are particularly significant for predicting local- and regional-scale changes to the cryosphere in response to on-going global climate warming (Raper and Braithwaite 2009). It is also possible to conduct comparison of historic volume change estimates with sea level measurements at high resolutions and to use this information to inform sea level forecasts (e.g. Nuth *et al.* 2007; Kjeldsen *et al.* 2015).

5. Debates and issues in trimline research

The early use of trimlines was for addressing the glacial refugia debate, assessing whether ice free summits might have acted as refuge for flora and fauna during glaciations (e.g. Ives *et al.* 1976). Trimlines were used to locate palaeo nunataks. This interpretation was supported by field investigations on the relative degree of weathering above and below British, Irish and Scandinavian trimlines (e.g. McCarroll *et al.* 1995; Dahl, S.-O. *et al.* 1996; Ballantyne 1997; Ballantyne *et al.* 1997/ 1998a/b; Ballantyne 1998; Lamb and Ballantyne 1998; Stone *et al.* 1998; McCarroll and Ballantyne 2000; Ballantyne and Hallam 2001; Rae *et al.* 2004; Ballantyne *et al.* 2006; Ballantyne *et al.* 2007; Nesje *et al.* 2007; Ballantyne *et al.* 2008; Ballantyne *et al.* 2011). These investigations were used to rule out alternative hypotheses of trimline formation, particularly that the trimlines represented changes in weathering conditions as ice surfaces lowered during deglaciation (Ballantyne 1998). However, the relative degree of weathering across a trimline was insufficient to discard a subglacial theory of trimline formation; that trimlines can form at the boundary between areas of erosive warm-based ice and areas of cold-based ice. To rule out the subglacial formation at thermal boundaries, researchers considered the morphology of the trimlines and tended to conclude in favour of an ice marginal origin. This conclusion was reached for three reasons: 1) the trimlines were deemed to be too sharp to be thermal; 2) the lack of an increase in trimline altitude on the stoss side of mountains compared to a decreased altitude, or 'pressure shadow', on the lee side, which would have indicated the high glacial velocities associated with warm-based ice; and 3) the regular decline of trimline altitudes along former flow lines was thought to be diagnostic of ice marginal formation (Ballantyne *et al.* 1997; Ballantyne *et al.* 1998a). The results of early cosmogenic nuclide dating studies were also supportive of the ice marginal hypothesis (e.g. Stone *et al.* 1998), although it was not possible to completely exclude a thermal origin.

The ice marginal interpretation of glacial trimlines found particular favour within the community of 'small British-Irish Ice Sheet (BIIS)' proponents, who concluded that at the LGM ice did not extend out to the continental shelf break (e.g. Bowen *et al.* 1986; Bowen *et al.* 2002). This reconstruction required relatively thin ice cover in Scotland, which would mean that many mountains remained above the ice surface as nunataks (Stone *et al.* 1998). The abundance of trimlines in the west and north of Scotland was taken to support the 'small BIIS' reconstruction because these features were interpreted as ice marginal and therefore thought to indicate a large number of palaeo nunataks (e.g. Ballantyne *et al.* 1997; Ballantyne *et al.* 1998a; Lamb and Ballantyne 1998).

Early numerical ice sheet modelling had suggested a larger BIIS, with fully submerged mountains in Scotland (e.g. Boulton *et al.* 1977), indicating that the trimlines of this area were of thermal origin. Later modelling utilised new understandings of the deformation of sediments beneath ice sheets, which was thought to provide lower basal resistance to flow and generate faster ice velocities. Increased flow rates in the new models yielded a thinner ice sheet and suggested the existence of nunataks, supporting the ice marginal interpretation of Scottish trimlines (Boulton *et al.* 1991; Lambeck 1993; Lambeck 1995). By the 1990s empirical and modelling studies had converged in support of the small BIIS theory and the interpretation of BIIS trimlines as ice marginal landforms (Ballantyne 2010).

Meanwhile, offshore geomorphological mapping and sedimentological studies were leading some authors to challenge the 'small BIIS' reconstruction and suggest that the last BIIS glaciation did reach the continental shelf break (e.g. Sejrup *et al.* 2005; Bradwell *et al.* 2008). This contrasting 'large BIIS' theory has been supported by a new phase of trimline dating that has favoured a thermal origin for many glacial trimlines, indicating a thicker and more spatially extensive ice sheet. Ballantyne and Hall (2008) demonstrate this shift in trimline interpretations with their reconstruction of the ice thickness in Caithness and east Sutherland, northern Scotland, using cosmogenically dated trimlines. Their dates and geomorphological evidence led them to identify a thermal origin for these trimlines and to suggest that the presence of nunataks in the area during the LGM was unlikely. Other studies in north-west Scotland have also supported the 'large BIIS' reconstruction and identified examples of thermal trimlines (e.g. McCormack *et al.* 2011; Fabel *et al.* 2012).

Recent numerical ice sheet modelling studies have also supported the 'large BIIS' theory (Boulton and Hagdorn 2006; Hubbard *et al.* 2009; Edwards *et al.* 2017). Both Boulton and Hagdorn (2006) and Hubbard *et al.* (2009) modelled the entire BIIS at the LGM and both studies considered the trimline evidence of western Scotland, as presented by Ballantyne *et al.* (1998a), to be of vital importance in constraining the accumulation area ice thickness. However, both noted that a thermal origin for these trimlines was possible and neither were able to force their models to conform to the ice thickness estimates produced from Scottish trimlines by Ballantyne *et al.* (1998a). These modelling studies therefore concluded that Scottish trimlines in most mainland locations represented palaeo thermal boundaries and were not ice marginal features.

Application of cosmogenic dating to new study areas has led to the identification of thermal trimlines in other regions of the BIIS. For example, in Ireland (Ballantyne *et* *al.* 2008; Ballantyne *et al.* 2011; Stone and Ballantyne 2015), Wales (Glasser *et al.* 2012) and the Lake District (Ballantyne *et al.* 2009). The thermal theory is now recognised to have been the dominant process of trimline formation beneath central areas of the BIIS during the LGM (Ballantyne 2010). However, trimlines associated with the Younger Dryas in Britain and Ireland are still thought to be ice marginal features (e.g. Stone and Ballantyne 2006) and debate continues about the correct interpretation of some trimlines in areas of rugged terrain (McCarroll 2016; Clark, C.D. *et al.* 2018; e.g. Barth *et al.* 2016).

The example of the debate surrounding BIIS trimline interpretation illustrates that both ice marginal and thermal trimlines are possible and can exist within the same ice mass (Ballantyne 2010). This indicates that trimlines in Quaternary settings can no longer be assumed to be ice marginal features. Outside the British Isles, there has been less extensive application of cosmogenic nuclide dating to Quaternary trimlines and there are few areas where trimline-based reconstructions and ice sheet modelling have been conducted in such close association, the European Alps being a notable exception (Seguinot et al 2018). However, the conclusions of BIIS trimline research suggest that care must be taken when interpreting Quaternary trimlines associated with the accumulation areas of ice sheets or ice caps, where the thick ice can include areas of differing thermal regime.

At present, specific modes of trimline expression have not been demonstrated to be associated with either ice marginal or thermal trimline formation. However, there may be links between trimline expression and the processes of trimline formation; for example, all vegetation trimlines studied so far have been identified as ice marginal (e.g. Wolken *et al.* 2005; McKinzey *et al.* 2004; Kelley *et al.* 2012;). Weathering limits, on the other hand, have been identified as both ice marginal (e.g. Ballantyne *et al.* 1997; Ballantyne *et al.* 1998a; Stone *et al.* 1998) and thermal (e.g. McCormack *et al.* 2011; Fabel *et al.* 2012), which perhaps indicates that these are not diagnostics of a particular process of trimline formation. Further research into the factors affecting trimline formation may help to explain the links between the mode of their expression and the process of formation, which would assist in the distinguishing ice marginal from subglacial trimlines.

The preservation potential of glacial trimlines has received little attention in the literature but this is a factor that may be related to processes of timeline formation and could influence the interpretation of glacial trimlines. It is common for the relative sharpness of trimlines to be described; although this is most often used to suggest that sharper trimlines are ice marginal (e.g. Ballantyne *et al.* 1997; Ballantyne *et al.* 1998a) and not generally to considered to be linked to post-glacial trimline modification. Few papers go into detailed discussion of the factors affecting trimline preservation in their study area or into description of the relative preservation of the different modes of trimline expression. A rare exception is Kelly *et al.*'s (2004) Quaternary trimline mapping in the European Alps. They found that erosional trimlines were best preserved where the bedrock resists weathering and that preservation is poor where bedrock is easily weathered and particularly where the bedrock is layered. This finding caused them to research the geology of their study area in greater detail and to use this information to aide in the interpretation of their trimlines. Further research along these lines may highlight other variables that affect trimline preservation and may aide in the interpretation of different modes of trimline expression.

Research has yet to consider the possibility of trimline preservation beneath overriding ice cover. However, the fact that trimlines are common components of palimpsest glacial landscapes, comprising landforms from multiple glaciations, suggests that study of the impact of overriding ice on trimlines may aide in the relative dating and interpretation of these features.

It is possible that the distribution of different trimline expressions could be indicative of trimline preservation potential in different climates, glaciological settings (ice marginal vs subglacial) or lithologies. If patterns of different trimline expressions could be linked to the period of time they have been exposed to weathering, this may allow for relative dating of trimline features. Further study into trimline preservation and expression in different climatic and geological settings is required to improve understandings of the way that trimline expression changes through time.

No study has so far presented any attempt to catalogue all observable modes of trimline expression or to explore patterns in the distribution of different types of glacial trimline. Some existing terminology exists to describe the expression of trimlines, such as 'vegetation trimline' or 'weathering limit', but many observable modes of trimline expression have no specific terms and have not been considered in the literature. This lack of a descriptive terminology may be hampering research into trimline distribution, formation, and preservation and could be leading to an artificial focusing of work on modes of trimline expression that are already well-described and associated with an established terminology.

Establishing synchroneity between trimline features and between trimlines and other associated glacial features is another proven area of difficulty. Even in a small group of valleys there may be multiple separate trimlines and it is often not clear which trimlines formed at the same time. On a regional scale, attempts have been made to link together trimlines of assumed synchronous ages in order to reconstruct regional glaciation or equilibrium line altitude positions (e.g. Kelly *et al.* 2004). However, at present there is no standardised method for establishing trimline synchroneity and researchers have largely relied on morphological or altitudinal similarities (Kelly *et al.* 2004). Studies using cosmogenic nuclide dating have linked trimlines of similar ages (e.g. Ballantyne *et al.* 2007; Fabel *et al.* 2012), but the error in the dating method is often too large to do this with any confidence.

Whilst interpreting trimline expression and problems of establishing trimline synchrononeity are significant, arguably the most important problems lie with the underlying identification and mapping of the trimlines. There are some published methods for the identification and mapping of trimlines (e.g Thorp 1981; 1986; 1987; Csatho *et al.* 2005) but these are specific to their study areas and there exists no generalised guidance for good-practice in trimline mapping. Also, trimlines are often very faintly expressed and can be easily confused with non-glaciogenic linear features. In particular, geological strata and palaeo lake or marine shorelines can appear very similar to trimlines in remotely sensed imagery and even in the field. Furthermore, the limited study of the preservation potential of trimlines means that little is known about how trimline expression may change through time. We suspect that many trimlines may be being overlooked where they are subdued or otherwise expressed in an atypical manner for their location. Better understanding of trimline formation and improved mapping methods including the use of secondary data, such as geological maps, alongside field validation and cosmogenic dating may allow for more confident identification of glacial trimlines, particularly distinguishing them from non-glaciogenic features in remotely sensed imagery, and improve the accuracy of trimline mapping.

In many cases, the presentation of a geomorphological map is the only clear description given of individual trimlines with many not providing detailed trimline mapping, but rather just marking their locations using a generic symbol (e.g. Kelly *et al.* 2004 used single spots to mark individual trimline locations). Some studies present field photographs of key trimlines (e.g. Kelly *et al.* 2004; Nesje *et al.* 2007; Forman *et al.* 2007; Glasser *et al.* 2011), but this is not standard practice. The shape and deflection of trimlines in relation to local topography might contain information about the processes of trimline formation and permit correlation across valleys. We suggest that good practice in trimline research would be for more detailed mapping of trimlines (e.g. Figure 8), and this information being presented in publications in order to aid growth in knowledge of their shape and spatial properties rather than just their existence and elevation.

The one aspect of individual trimline morphology to have been widely discussed is the slope of ice marginal trimlines, which is considered when establishing trimline synchroneity to reconstruct the ice surfaces across several valleys or massifs (e.g. Ballantyne *et al.* 1997; Ballantyne *et al.* 1998b). Additionally, the record of ice thickness gradients preserved in patterns of trimline slope has been used to deduce palaeo precipitation gradients and to estimate palaeo ELA (e.g. Glasser *et al.* 2008).

Relative to the likely widespread distribution of trimlines (e.g. peruse Google Earth images say in the Karakorum, Torngat Mountains, or around Greenland) it is obvious that they have been under-studied given the limited distribution of trimlines reported in the literature (Figure 7). At a regional scale, topography and geology are likely to influence the distribution of trimlines due to the significant impact of these factors on patterns of glacial erosion and deposition. Some authors have mentioned the impact of geology on trimline expression (e.g. McCarroll *et al.* 1995; Kelly *et al.* 2004) but discussion of the impact on trimline distribution tends to be limited and the impact of topography has been similarly overlooked. Barring brief mention of the concentration of trimlines on spurs by Thorp (1981), hardly any papers have discussed the relationship between topography and trimline distribution within a study area. If further research can better determine the impact of topography and geology on trimline distribution, this information may be significant for the identification and mapping.

In summary, previous research has been largely focused on identifying, mapping and interpreting glacial trimlines with a view to use these features in ice surface morphology and ice thickness reconstructions. This narrow focus has led to several under-researched areas, particularly: processes of trimline formation (beyond the ice marginal or thermal debate); the expression of glacial trimlines; the preservation of trimline features; the morphology or shape of individual trimlines; and the wider distribution of glacial trimlines. These areas of research have the potential to resolve issues with identifying and mapping trimlines and could also help to establish synchroneity between groups of trimlines and between trimlines and other glacial features.

6. A scheme for trimline definition and classification

The terminology surrounding glacial trimlines is complex and non-standardised. This confusion leads to a lack of clarity in their discussion and in particular the blurred distinction between the description of an observable feature (trimline) and its interpretation, say as an ice-marginal trimline, is not helpful. Also, the existing terminology is insufficient to describe different modes of trimline expression. To mitigate the above points, a new and more precise definition for the term 'glacial trimline' is here suggested:

"Glacial trimlines are glaciogenic features expressed as a break or transition in the vegetation, weathered material, erosion pattern, deposited material, or truncated slope landforms (e.g. talus cones, gullies) on the slopes of a glacierised or glaciated valley."

The above definition of 'glacial trimline' allows room for both the concept of trimlines as linear features and as areas of transition between two landsurface zones. The definition also allows for both lateral and frontal trimline features – 'valley slopes' need not necessarily be lateral but can also refer to the valley floor in front of a glacier or former glacier. Using the above definition, a 'glacial trimline' can be of either ice marginal or thermal origin; both of these processes of trimline formation are glaciogenic so both can be described as 'glacial trimlines' (Figure 9).

However, the above definition implies a degree of interpretation to suggest that a given trimline feature is glaciogenic. In order to ensure adequate separation of pure description from any interpretation, the term 'apparent trimline' is suggested for a linear trace or transition on the side of a glacierised or glaciated valley of unknown origin (Figure 9).

By distinguishing between 'apparent trimlines' and 'glacial trimlines' it is hoped that a better separation between description and interpretation of trimline features can be achieved. Once an apparent trimline is determined to be of glacial origin, further interpretation steps can be used to identify it as an 'ice marginal trimline' or a 'thermal trimline'. These terms are preferred to the various alternatives used in the literature (Table 1) because their meaning is clear and their usage will provide greater standardisation and clarity.

Glacial trimline expressions vary and have been called by a wide range of terms in the literature (Table 1). In Figure 10a an attempt at summarising the observable modes of glacial trimline expression is presented, alongside specific terms for each of these types. Associated ice marginal features, such as lateral moraines and kame terraces, are also mentioned. These features have different processes of formation to glacial trimlines but their interpretation as ice marginal features and their uses in reconstructions are very similar to those of glacial trimlines, so it is important that these features are kept in mind when mapping and classifying trimlines.

By having individual terms for specific modes of glacial trimline expression it will be easier to clearly describe a given trimline feature and to distinguish and compare multiple glacial trimlines, as well as to use trimlines in conjunction with associated ice marginal features. The classification in Figure 10a has undergone a test application to the trimlines of central western Spitsbergen and was found to be both easily usable and a complete classification, covering all of the observable modes of trimline expression in the study area (Rootes 2018; Chapter 4). By presenting this initial classification here, it is hoped further research will be stimulated that will ultimately lead to a more robust and transparent terminology for glacial trimline expression.

7. Conclusions

Glacial trimlines are glaciogenic features expressed as a break or transition in the vegetation, weathered material, erosion pattern, deposited material, or slope features on the slopes of a glacierised or glaciated valley. We suggest this is a useful general definition, and from our literature review have compiled a terminology that is appropriate for describing different type of trimlines (Figure 10). These terms have been trialled and found to work adequately in an investigation of trimlines in Svalbard (Rootes 2018; Chapter 4). We suggest that adoption of a clear and standardised terminology for glacial trimlines will help future research investigations and in particular, a clear distinction is advisable between pure description and terms implying a degree of interpretation.

Glacial trimlines are under-studied compared to other types of glacial geomorphological features, despite their abundance and significance for the production of 3D palaeoglaciological reconstructions. Trimlines are particularly important because they record both the ice margin position and a measure of the ice thickness at their time of formation, making them valuable empirical constraints on ice volume changes. Three-dimensional reconstructions are an increasingly important output of palaeoglaciology because they can be used for testing and refining numerical glacial models and they can also be used to estimate the palaeo Equilibrium Line Altitude (ELA), permitting inference of climate changes. Better use of glacial trimlines, therefore, has the potential to improve understanding of the geomorphological signature left by glaciers in rugged terrain and to increase the accuracy and confidence of 3D palaeoglacial reconstructions based on this empirical evidence.

Overall, there has been a paucity of research into trimline features themselves, particularly their formation, expression, preservation, morphology and distribution. The limited picture that we have of glacial trimlines is potentially leading to inaccurate interpretations of Quaternary and historic trimline features. Additionally, the narrow focus of trimline research in space and time, as well as the limited range of trimline expressions that have been studied, suggests that expanding the scope of trimline research may be fruitful.

There is a large potential for further research into glacial trimlines, particularly given the marked clustering of trimline research in North-West Europe and North America and the lack of detailed studies in other areas (Figure 7). Examples of previously unidentified trimlines in new areas are easy to find using readily available tools, such as Google Earth, and some examples are given in Figure 11. Suggestions for potentially fruitful study areas for future trimline research include but are not limited to: the Younger Dryas in Scotland; LGM in the European Alps; LGM in the Torngat mountains of Canada; and recent ice margin fluctuations in the Karakorum (e.g. Figure 11).

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Table 1 (next page) – terms used to describe glacial trimlines

Term group	Term	Definition	Papers using this term
Generic linear	Trimline, (Trim-line) (Trim line)	Glasser *et al.* (2005) provide a rare definition: "Sub-horizontal lines on valley sides separating areas of non-vegetated and vegetated land or areas covered by different types of vegetation" (pp.266). More often this term is undefined. Generally, a more specific term is used initially before resorting to just 'trimline' for the core of the paper. Commonly more specific terms are returned to in the discussion and conclusion. Also, it is quite common for a paragraph to start with a more specific term and then transition to using just 'trimline'. Indirectly defined by Cockburn and Summerfield (2004, pp.18): "Geomorphic indicators of previous ice levels range from clearly defined trim lines to more equivocal weathering limits which may reflect other zones of process transition, such as postglacial differential weathering or englacial boundaries between wet-based eroding ice and non eroding frozen-bed ice"	Lawrence (1950a); Lawrence (1950b); Nicols and Miller (1951); Heusser *et al.* (1954); Thorp (1981); Thorp (1986); Nesje *et al.* (1987); Nesje *et al.* (1988); Thomsen and Winding (1988); Huber (1989); Reed (1989); Ballantyne (1990); Lawson (1990); Nesje and Dahl, S.-O. (1990); Orombelli *et al.* (1990); MacCarroll and Nesje (1993); Kleman (1994); Ballantyne (1994a/b); Ballantyne and Harris (1994); Locke (1995); McCarroll *et al.* (1995); Brook *et al.* (1996); Dahl, S.-O. *et al.* (1996a/b); Ballantyne (1997); Ballantyne *et al.* (1997); Lowe and Walker (1997); Ballantyne (1998); Ballantyne *et al.* (1998a/b); Florineth (1998); Florineth and Schluchter (1998); Lamb and Ballantyne (1998); Stone *et al.* (1998); Armienti and Baroni (1999); McCarroll and Ballantyne (2000); Ballantyne and Hallam (2001); Kaplan *et al.* (2001); Walden and Ballantyne (2002); Traczyk and Migoñ (2003); Clark, C.D. *et al.* (2004); Cockburn and Summerfield (2004); Kelly *et al.* (2004); McKinzey *et al.* (2004); Cockburn and Summerfield (2004); Rae *et al.* (2004); Reuther *et al.* (2004); Csatho *et al.* (2005); Evans *et al.* (2005); Fiebig *et al.* (2005); Glasser *et al.* (2005); Kuhlemann *et al.* (2005); Wolken *et al.* (2005); van der Veen and Csatho (2005); Boulton and Hagdorn (2006); Fjellanger *et al.* (2006); Gosse *et al.* (2006); Hubbard *et al.* (2006); Linge *et al.* (2006); Stone and Ballantyne (2006); Ackert *et al.* (2007); Ballantyne (2007); Ballantyne *et al.* (2007); Forman *et al.* (2007); Goodfellow (2007); Harrison *et al.* (2007); Nesje *et al.* (2007); Reuther *et al.* (2007); Ballantyne *et al.* (2008); Ballantyne and Hall (2008); Baroni *et al.* (2008); Brooks *et al.* (2008); Castho *et al.* (2008); Fretwell *et al.* (2008); Glasser *et al.* (2008); Goehring *et al.* (2008); Hormes *et al.* (2008); Van der Beek and Bourbon (2008); Ballantyne *et al.* (2009); Ballantyne (2010); Benn and Evans (2010); Benn and Hulton (2010); Chiverrell and Thomas (2010); Hughes *et al.* (2010); Möller *et al.* (2010); Ackert *et al.* (2011); Ballantyne *et al.* (2011); Glasser *et al.* (2011); McCormack *et al.* (2011); Glasser *et al.* (2012); Fabel *et al.* (2012); Kelley *et al.* (2012); Kuchar *et al.* (2012); Tantardini *et al.* (2013); Gourronc *et al.* (2014); Lee *et al.* (2014); Loibl *et al.* (2014); Nixon and England (2014); White and Fink (2014); Ballantyne and Stone (2015); Hannesdóttir *et al.* (2015); Kjeldsen *et al.* (2015); Barth *et al.* (2016); Bickerdike *et al.* (2016); Evans (2016); McCarroll (2016); Edwards *et al.* (2017); Deswal *et al.* (2017); Hannah *et al.* (2017) Sugden *et al.* (2017); Badino *et al.* (2018); Baroni *et al.* (2018); Bjørk *et al.* (2018); Campos *et al.* (2018); Charalampidis *et al.* (2018); Clark, C.D. *et al.* (2018); Haubner *et al.* (2018); Iturrizaga (2018); Izagirre *et al.* (2018); Kelley *et al.* (2018); Sharma *et al.* (2018); Kozamernik *et al.* (2018); Levy *et al.* (2018); Makos *et al.* (2018); Marr *et al.* (2018);

			Marrero *et al.* (2018); Meier *et al.* (2018); Pearce *et al.* (2018); Philipps *et al.* (2018); Bjørk *et al.* (2018); Seguinot *et al.* (2018); Serrano *et al.* (2018); Sharma and Shukla (2018); Shennan *et al.* (2018); Temovski *et al.* (2018); Aa and Sønstegaard (2019); Carrivick *et al.* (2019); Kissick and Carbonneau (2019); Merritt *et al.* (2019); Schweinsberg *et al.* (2019); Yde *et al.* (2019); Bayrakdar *et al.* (2020)
	Glacial trimline	Undefined. Can be used to refer to an erosional feature that is presumed to approximate the palaeo ice margin (e.g. Kelly *et al.* 2004 p.61).	Kelly *et al.* (2004); Sugden *et al.* (2005); Nesje *et al.* (2007); Hormes *et al.* (2008); Oberholzer *et al.* (2008); Van der Beek and Bourbon (2008); Gourronc *et al.* (2014); Larsen *et al.* (2014); Lee *et al.* (2014); Makos and Niychoruk (2011); Makos *et al.* (2013); Zasadni and Kłapyta (2014); Wirsig *et al.* (2016a/b); Sugden *et al.* (2017); Makos *et al.* (2018); Kissick and Carbonneau (2019)
Generic zonal	Trimzone/ trimline zone	Terms used interchangeably to refer to the area between the trimline and the modern ice margin.	Thomsen and Winding (1988); Reed (1989); Csatho *et al.* (2005); Csaho *et al.* (2008); Forman *et al.* (2007); Zasadni and Kłapyta (2014); Wirsig *et al.* (2016a); Philipps *et al.* (2018)
Ice mass	Glacier trimline	Undefined. Trimline associated with a glacier.	Csatho *et al.* (2005); van der Veen and Csatho (2005)
	Ice sheet trimline	Undefined. Trimline associated with a palaeo ice sheet (see Ballantyne *et al.* 1998b, pp.65).	Lawson (1990); Ballantyne (1994b); McCarroll *et al.* (1995); Ballantyne (1997); Ballantyne *et al.* (1997); Ballantyne (1998); Ballantyne *et al.* (1998a/b); Lamb and Ballantyne (1998)
	Ice-cap trimlines	Undefined. Trimline associated with palaeo ice caps.	Wolken *et al.* (2005)
Age	Palaeo-trimline	Undefined. Trimlines associated with Quaternary ice masses.	Hubbard *et al.* (2009)
	Historical trimline	Undefined. Trimlines associated with Holocene glacial fluctuations.	Levy *et al.* (2018)
Study area significance	Regional trimline	Undefined. Used by Nesje *et al.* (2007, pp.234) for the average trimline altitude across their study area.	Nesje *et al.* (2007)
Ice marginal interpretation	Ice-marginal trimline	Undefined but used to distinguish the feature in question from englacial/subglacial thermal boundaries (Nesje *et al.* 2007, pp.228).	Nesje *et al.* (2007)
	Periglacial trimline	Defined as marking "the maximum level to which glacier ice has eroded or 'trimmed' a pre-existing zone of frost-weathered rock or debris on mountain slopes" (Ballantyne and Harris 1994, p.182. Re-stated by Ballantyne *et al.* (1997, pp.227; 2011,	Reed (1989); Ballantyne (1990); Ballantyne (1994a); Ballantyne and Harris (1994); Bennett (1994); McCarroll *et al.* (1995); Dahl, S.-O. *et al.* (1996a/b); Ballantyne (1997); Ballantyne *et al.* (1997); Ballantyne (1998); Ballantyne *et al.* (1998b); Lamb and Ballantyne (1998); Stone *et al.* (1998); Ballantyne (1999a/b); McCarroll and Ballantyne (2000); Ballantyne and Hallam (2001); Hughes (2002); Walden and Ballantyne (2002); Rae *et al.* (2004); Evans *et al.* (2005); Sugden *et al.* (2005); Ballantyne *et al.* (2006); Ballantyne *et al.* (2006); Hughes

		pp.3834) and Ballantyne (2010, pp.524)). See list of identifying features in Benn and Evans (2010, pp.620).	*et al.* (2006); Stone and Ballantyne (2006); Ballantyne (2007); Ballantyne *et al.* (2007); Nesje *et al.* (2007); Ballantyne *et al.* (2009); Ballantyne (2010); Benn and Evans (2010, pp.619-620); Ballantyne *et al.* (2011); Fabel *et al.* (2012); Bickerdike *et al.* (2016); Evans (2016); McCarroll (2016); Wirsig *et al.* (2016b); Marr *et al.* (2018)
	Glacier limit/ glacial limit/ limit of glaciation	Undefined. Location of the palaeo ice margin as recorded by a trimline.	Sissons (1974); Grant (1977); Traczyk and Migoñ (2003); Reuther *et al.* (2004); Gosse *et al.* (2006); Reuther *et al.* (2007); Benn and Evans (2010, pp.619); Hughes *et al.* (2012); Iturrizaga (2018); Izagirre *et al.* (2018); Merritt *et al.* (2019); Hughes *et al.* (2019)
	Ice sheet limit	Undefined. Used to refer to both the lateral and vertical dimensions of the palaeo ice sheet.	Brook *et al.* (1996); Fretwell *et al.* (2008); Chandler *et al.* (2018)
	Periglacial zone	Undefined. Used to refer to areas with evidence of periglacial weathering.	Ballantyne (1998); Marr *et al.* (2018)
Glacial surging interpretation	Surge trimline	Defined as being: “distinguished from traditional trimlines by being located further down-glacier and higher on the valley walls than is expected from a traditional glacier advance” (Yde *et al.* 2019, pp.94).	Yde *et al.* (2019)
Subglacial or thermal interpretation	Englacial trimline	Defined as "marking the approximate upper boundary of warm-based ice" (Ballantyne 2010, pp.525).	Ballantyne (2010)
	Subglacial zone	Undefined but used to describe areas with subglacial landforms. Often used alongside 'nonglacial zone', which describes the area with weathering or periglacial landforms.	Hattestrand and Stroeven (2002)
	Thermal trimline	Defined as representing a "thermal boundary between cold-based and wet-based ice below an ice sheet, rather than a former ice surface" (Benn and Evans 2010, pp.620).	Benn and Evans (2010, pp.620); Zasadni and Kłapyta (2014)
Type of trimline expression	Vegetation trimline	Defined as "light-toned, barely vegetated terrains displaying abrupt outer margins extend back to modern glaciers and ice caps" by Wolken *et al.* (2005, pp.343).	Knight *et al.* (1987); Wolken *et al.* (2005); Harrison *et al.* (2007); Benn and Evans (2010, pp.619); Kelley *et al.* (2012); Meier *et al.* (2018); Stokes *et al.* (2018)
	Forest trimline	Early equivalent to 'vegetation trimline'. Defined by Lawrence (1950a, pp.243) “the line representing	Lawrence (1950a); Lawrence (1950b); Mathews (1951); Nicols and Miller (1951)

	the maximum position attained by the ice front, where the forest was sheared off by the ice”	
Lichen trimline	Undefined, but expressed solely through a contrast in lichen cover.	Mahaney (1987); Mahaney (1991)
Vegetation-free zone/ lichen-free zone	Undefined. Used by Wolken *et al.* (2005) to describe the areas within their vegetation trimlines.	Wolken *et al.* (2005)
Weathering trimline/ limit/ boundary/ contrast	Defined by Boulton and Hagdorn (2006, pp.3361) as being "where glacially eroded surfaces at lower elevations gave way to weathered rock surfaces and ‘‘frost debris’’ at higher elevations" and by Ballantyne and Harris (1994, pp.182) as "the boundaries between [weathering] zones". Used interchangeably with 'periglacial trimline' by Ballantyne *et al.* (1997; 2009).	Ballantyne *et al.* (1987); Nesje *et al.* (1987); Ballantyne (1990); Nesje and Dahl, S.-O. (1990); Ballantyne (1994a); McCarroll *et al.* (1995); Brook *et al.* (1996); Ballantyne *et al.* (1997); Ballantyne *et al.* (1998b); Lamb and Ballantyne (1998); Stone *et al.* (1998); Walden and Ballantyne (2002); Cockburn and Summerfield (2004); Marquette *et al.* (2004); Rae *et al.* (2004); Evans *et al.* (2005); Ballantyne *et al.* (2006); Boulton and Hagdorn (2006); Fjellanger *et al.* (2006); Ballantyne *et al.* (2009); Marr *et al.* (2018); Kissick and Carbonneau (2019)
Weathering zone/ frost-weathered zone/ zone of frost-weathering/ weathered zone	Defined by Ballantyne (1994a, pp.182): "A related concept is that of weathering zones: as successive trimlines delimit altitudinal zones that have been exposed to weathering processes for different lengths of time, then the degree of rock weathering and soil development should be more advanced in the zone above any trimline than in the zone below." Also, by Clark, P.U. *et al.* (2003, pp.617) as "units of the land surface that are identified by distinct weathering features".	Løken (1962) [in French]; Boyer and Pheasant (1974); Ives (1975); Ives (1976); Ives *et al.* (1976); Grant (1977); Ives (1978); Dyke (1979); Reed (1989); Nesje and Dahl, S.-O. (1990); Ballantyne (1994a); Kleman (1994); MacCarroll *et al.* (1995); Ballantyne (1997); Ballantyne *et al.* (1997); Ballantyne (1998); Ballantyne *et al.* (1998a/b); Briner *et al.* (2003); Clark, P.U. *et al.* (2003); Rae *et al.* (2004); Sugden *et al.* (2005); Fjellanger *et al.* (2006); Gosse *et al.* (2006); Goodfellow (2007); Goehring *et al.* (2008)
Weathering surface	Undefined. Meaning appears to be similar to 'weathering zone'.	Kverndal and Sollid (1993)
Blockfield boundary/ block-field boundary	The margin of a periglacial blockfield. Defined by Goehring *et al.* (2008, pp.333): "represents an englacial thermal boundary between frozen bed nonerosive ice above and a wet-bed region below	Dahl, R. (1966b); Brook *et al.* (1996); Goehring *et al.* (2008)

	that was progressively more erosive with increasing ice thickness."	
Erosional trimline/ limit/ boundary	Undefined but generally used interchangeably with 'periglacial trimline' or 'trimline'.	Nesje and Dahl, S.-O. (1990); Orombelli *et al.* (1990); Ballantyne (1998); Ballantyne *et al.* (1998a/b); Kaplan *et al.* (2001); Walden and Ballantyne (2002); Ballantyne (2007); Oberholzer *et al.* (2008); Möller *et al.* (2010); Sugden *et al.* (2017); Levy *et al.* (2018)
Erosional zone/ scoured zone/ limit of effective glacial erosion	Undefined. Used to refer to areas with clear evidence of flowing warm-based ice.	Ballantyne (1997); Ballantyne *et al.* (1998a/b); Hattestrand and Stroeven (2002); Linge *et al.* (2006); Goodfellow (2007); Nesje *et al.* (2007); Fu *et al.* (2013); Fu *et al.* (2019); Merritt *et al.* (2019)
Ice-scoured trimline	Undefined. Presumably similar to an erosional trimline.	Harrison *et al.* (2007)
Trimline moraine	Pictorially defined as a terminal or lateral-frontal moraine system that outlines the former ice margin position (Benn and Evans 2010, pp.513).	O'Cofaigh *et al.* (2003); Benn and Evans (2010, pp.513)
Boulder limit/ limit of glacial erratics	Undefined. Used to describe the upper bound of glacial erratic distributions. Suggested to indicate a thermal or ice flow boundary.	Mackintosh *et al.* (2007)
Depositional trimline	Undefined. Used to describe limits of glacial erratics and other deposition.	Marrero *et al.* (2018)

Table 2 (next page) – locations of research into glacial trimlines

Region	Location	Sub-location	Paper count	References
Britain and Ireland	British Isles		24	Geikie (1874); Linton (1949); Boulton *et al.* (1977); Bowen *et al.* (1986); Nesje and Sjerup (1988); Lambeck (1993); Ballantyne (1994b); Lambeck (1995); Migoñ and Goudie (2001); Bowen *et al.* (2002); Clark, C.D. *et al.* (2004); Evans *et al.* (2005); Boulton & Hagdorn (2006); Fretwell *et al.* (2008); Hubbard *et al.* (2009); Ballantyne (2010); Chiverrell & Thomas (2010); Clark, C.D. *et al.* (2012); Kuchar *et al.* (2012); Bickerdike *et al.* (2016); Bickerdike *et al.* (2018a/b); Clark, C.D. *et al.* (2018); Shennan *et al.* (2018)
	Ireland	All	2	Ballantyne & Stone (2015); Shennan *et al.* (2018)
		North-West	1	Ballantyne *et al.* (2007)
		West	2	Ballantyne *et al.* (2008); Edwards *et al.* (2017)
		South-West	2	Ballantyne *et al.* (2011); Barth *et al.* (2016)
		East	1	Ballantyne *et al.* (2006)
	Scotland	All	7	Sissons (1967); Ballantyne (1984); Boulton *et al.* (1991); Bennett (1994); Ballantyne (1997); Ballantyne (1998); Merritt *et al.* (2019)
		Grampians	5	Stevens and Wilson (1970); Sissons (1974); Thorp (1981); Thorp (1986); Thorp (1987)
		Cairngorms	4	Sugden (1968); Sugden (1970); Ballantyne (1994b); Phillips *et al.* (2006)
		North-West; including Wester Ross	16	Gordon (1979); Ballantyne (1987); Reed (1989); Lawson (1990); McCarroll *et al.* (1995); Ballantyne *et al.* (1997); Ballantyne *et al.* (1998a/b); Stone *et al.* (1998); Ballantyne (1999a/b); Walden and Ballantyne (2002); Ballantyne & Hall (2008); Phillips *et al.* (2008); McCormack *et al.* (2011); Fabel *et al.* (2012)
		North-East	5	Godard (1965); Romans *et al.* (1966); Hall (1985); Hall and Sugden (1987); Glasser (1995)
		Southern	1	Ragg and Bibby (1966)
		Outer Hebrides	6	Geikie (1873); Geikie (1878); Ballantyne and Hallam (2001); Ballantyne *et al.* (2006); Stone and Ballantyne (2006); Ballantyne (2007)
		Inner Hebrides	7	Anderson and Dunham (1966); Ballantyne (1989); Ballantyne (1990); Ballantyne (1994); Dahl, S.-O. *et al.* (1996); Ballantyne *et al.* (1997); Stone *et al.* (1998)

Britain and Ireland	Wales	All	2	Jansson and Glasser (2005); Glasser *et al.* (2012)
		Snowdonia	3	Fearnside (1905); McCarroll and Ballantyne (2000); Hughes (2002)
	England	Dartmoor	1	Linton (1955)
		Lake District	4	Lamb and Ballantyne (1998); Ballantyne *et al.* (2009); Hughes *et al.* (2012); Hughes *et al.* (2019)
Central Europe	The Alps	All	2	Wirsig *et al.* (2016b); Seguinot *et al.* (2018)
		Central	1	Cohen *et al.* (2018)
		Swiss	5	Florineth (1998); Florineth & Schluchter (1998); Kelly *et al.* (2002); Kelly *et al.* (2004); Bini *et al.* (2009); Wirsig *et al.* (2016a)
		Austrian	1	*Charalampidis et al. (2018)*
		French	3	Mahaney (1987); Mahaney (1991); van der Beek & Bourbon (2008)
		Italian	3	Hormes *et al.* (2008); Tantardini *et al.* (2013); *Badino, et al. (2018)*
		Eastern/ South-eastern	2	Fiebig *et al.* (2005); Kozamernik *et al.* (2018)
	The Carpathians		5	Reuther *et al.* (2004); Reuther *et al.* (2007); Makos and Nitychoruk (2011); Makos *et al.* (2013); Zasadni & Kłapyta (2014)
	The Sudetes		1	Traczyk and Migoñ (2003)
Southern Europe	Iberian Peninsula		2	Campos *et al.* (2018); *Serrano et al. (2018)*
	The Apennines		1	Baroni *et al.* (2018)
	Balkans		4	Hughes *et al.* (2006); Hughes *et al.* (2010); Ribolini *et al.* (2017); Temovski *et al.* (2018)
	Corsica		1	Kuhlemann *et al.* (2005)
Eastern Europe	The Urals		2	Astakhov (2018); Svendsen *et al.* (2019)
	The Tatras		1	Makos *et al.* (2018)

Fennoscandia	All		2	Kleman *et al.* (1999); Fabel *et al.* (2002)
	Scandinavia		7	Wråk (1905); Linton (1949); Dahl, E. (1955); Dahl, E. (1961); Kleman (1994); Stroeven and Kleman (1999); Linge *et al.* (2006)
	Norway	All	9	Blytt (1876); Reusch (190); Ahlmann (1919); Nordhagen (1936); Gjærevoll (1963); Nordhagen (1963); Gjessing (1967); Mangerud (1973)
		North	11	Sørensen (1949); Grønlie (1953); Dahl, R. (1966a/b); Kverndal and Sollid (1993); Rea *et al.* (1996b); Whalley *et al.* (1997); Whalley *et al.* (2004); Fjellanger *et al.* (2006); Nesje *et al.* (2007); *Stokes et al. (2018)*
		South	7	Nesje *et al.* (1988); Nesje (1989); Nesje and Dahl, S.-O. (1990); Nesje *et al.* (1994); Lidmar-Bergström *et al.* (2000); Goehring *et al.* (2008); Marr *et al.* (2018)
		Central	2	Sollid and Sørbel (1979); Sollid and Reite (1983)
		Western	9	Dahl, E. (1948); Mangerud *et al.* (1979); Sollid and Sørbel (1979); Roaldset (1982); Nesje *et al.* (1987); Rye *et al.* (1987); McCarroll and Nesje (1993); Brook *et al.* (1996); *Aa & Sønstegaard (2019)*
		Svalbard	2	Henriksen *et al.* (2014); Rootes (2018)
	Sweden	North-West	6	Sernander (1896); Lagerbäck (1988a/b); Kleman (1992); Kleman and Stroeven (1997); Clarhäll and Kleman (1999)
		North-East	2	Hättestrand and Stroeven (2002); Stroeven *et al.* (2002)
		Southern	1	Kleman and Borgström (1990)
	Finland	Lapland	1	Kaitanen (1969)
	NW Russia	Around the White Sea	1	Larsen *et al.* (2014)

North Atlantic	Faroe Islands		1	Walden and Ballantyne (2002)
	Iceland	All	2	Norðdahl (1991); Hubbard *et al.* (2006)
		North	2	Norðdahl (1983); *Brynjólfsson et al. (2014)*
		Vatnajökull	1	*Hannesdóttir et al. (2015)*
	Greenland	All	5	*Gjærevoll and Ryvarden (1978); Weidick (1955); Sugden (1974); Ó Cofaigh et al. (2003); Kjeldsen et al. (2015)*
		West or South-West	11	*Weidick (1968); Weidick (1969); Weidick (1992); Kelley et al. (2012); Haubner et al. (2018); Kelley et al. (2018); Levy et al. (2018); Pearce et al. (2018); Philipps et al. (2018); Schweinsberg et al. (2019); Yde et al. (2019)*
		North-East	1	*Carrivick et al. (2019)*
		Jakobshavn	5	*Knight et al. (1987); Thomsen and Winding (1988); Csatho et al. (2005); van der Veen and Csatho (2005); Csatho et al. (2008)*
		Kangerlussuaq	1	*Forman et al. (2007)*
		Helheim	1	*Bjørk et al. (2018)*
Asia	Western Asia	Turkey	1	Bayrakdar *et al.* (2020)
	Tibet		2	Fu *et al.* (2013); *Loibl et al. (2014)*; Fu *et al.* (2019)
	Tian Shan		1	*Li and Li (2014)*
	Altai-Sayan		1	Blomdin *et al.* (2016)
	NW India		4	Lee *et al.* (2014); *Deswal et al. (2017); Sharma et al. (2018); Sharma and Shukla (2018)*
Africa	Morocco	High Atlas	1	Hannah *et al.* (2017)
New Zealand	South Island	Frans Josef Glacier	1	*McKinzey et al. (2004)*
South America	Patagonia	All	3	*Glasser et al. (2008); Glasser et al. (2011); Meier et al. (2018)*
		North	2	*Glasser et al. (2005); Harrison et al. (2007)*
		South	1	*Nicols and Miller (1951)*
	Cordillera Blanca		1	Iturrizaga (2018)
	Tierra del Fuego		2	Möller *et al.* (2010); *Izagirre et al. (2018)*

North America	All		6	Ives (1978); Sugden (1977); Sugden (1978); Dyke and Prest (1987); Kleman (1994); Briner *et al.* (2006b)
	Arctic Canada	All	1	Ó Cofaigh *et al.* (2003)
		Baffin Island	9	Boyer and Pheasant (1974); Ives (1975); Ives (1977); Sugden and Watts (1977); Dyke (1979); Bierman *et al.* (1999); Kaplan *et al.* (2001); Briner *et al.* (2005); Briner *et al.* (2006a)
		Queen Elizabeth Islands	2	Wolken *et al.* (2005); Nixon and England (2014)
	Eastern Canada	Torngat/ Ungava	8	Ives (1957); Ives (1958a); Ives (1976); Ives *et al.* (1976); Clark, P.U (1988); Clark, P.U (1991); Clark, P.U *et al.* (2003); Marquette et al (2004)
		Newfoundland	2	Grant (1977); Gosse *et al.* (2006)
		Labrador/ Québec	4	Leiber (1861); Ives (1958b); Løken (1962); Jansson (2005)
	Western Canada	Keewatin & NW Territories	2	Aylesworth and Shilts (1989a); Aylesworth and Shilts (1989b)
		British Columbia	1	Mathews (1951)
	Northern USA	Pacific North-West	1	Lawrence (1950a)
		New England	1	Bierman *et al.* (2015)
		Alaska	2	Heusser *et al.* (1954); Lawrence (1950b)
		Minnesota	1	Bierman *et al.* (1999)
		Washington	1	Briner and Swanson (1998)
		Wyoming	1	Anderson (2002)
		Montana	1	Locke (1995)
		Utah	1	Munroe (2006)
		Yellowstone	1	Pierce (1979)
		Yosemite	1	Huber (1989)

Antarctica	All		1	*Marrero et al. (2018)*
	West	All	1	Pollard and DeConto (2009)
		Peninsula	2	Bentley *et al.* (2006); Carrivick *et al.* (2012)
		Marie Byrd Land; including the Ohio Range	3	Sugden *et al.* (2005); Ackert *et al.* (2007); Ackert *et al.* (2011)
		Ellsworth Mountains	1	Sugden *et al.* (2017)
	East	Enderby Land	1	White and Fink (2014)
		Victoria Land	4	Orombelli *et al.* (1990); Armienti and Baroni (1999); French and Guglielmin (2002); Baroni *et al.* (2008);
		Mac. Robertson Land	1	Mackintosh *et al.* (2007)
		McMurdo Dry Valleys	3	Bruno *et al.* (1997); Stroeven and Kleman (1999); Oberholzer *et al.* (2008)
Conceptual/ Review/ Methods	[i.e. papers with no specific location]		16	Linton (1950); Ives (1974); Boulton (1979); Dahl, E. (1987); Sugden (1989); Dahl, E. (1992); Brunsden (1993); Kleman (1994); Cockburn & Summerfield (2004); Goodfellow (2007); Kleman & Glasser (2007); Benn and Hulton (2010); Evans (2016); McCarroll (2016); Rootes (2018); Ely *et al.* (2019)
Extra-terrestrial	Mars	Valles Marineris	2	Gourronc *et al.* (2014); Kissick *et al.* (2019)

Table captions

Table 1 – Terminologies used in the literature to refer to trimline features or zones. The wide range of terminology and the number of terms that lack a formal definition might be hampering discussion of glacial trimlines and limiting the progress of research.

Table 2 – Full list of the papers used to produce this literature review, grouped by study location. Both Quaternary or older (normal text) and historic (italics) papers are listed. From this table, and the maps in Figure 7, it is clear that there has been significant clustering of trimline studies in certain locations. It is also obvious from this table that the majority of trimline papers are solely Quaternary studies. This is particularly true because many of the highlighted historic papers also include some study of Quaternary glaciations, which is rarely true in reverse.

Figure captions

Figure 1 – Example of a glacial trimline (white dashed) recording a former margin position of the Mer de Glace in the Mont Blanc area, France. This trimline is an example of a vegetation and slope process contrast that records both the lateral ice margin position and the ice thickness at the time of trimline formation. The largely vegetation-free area between the modern ice margin (solid) and the trimline (white dashed) is termed the 'trimzone' (arrow). The date of the trimline is known from historical artwork and written documents. From these two dated ice margin positions it is possible to calculate rates of volume loss since the Little Ice Age, which peaked in this area at around the time of trimline formation.

Figure 2 – The trimzone surrounding Jakobshavn Isfjord in western Greenland. Csatho et al. (2008) identified the trimzone (orange) using analysis of the spectral reflectance of different land surfaces. In this case the trimzone is differentiated by a reduced lichen density compared to the surrounding area. They dated the outer edge of the trimzone, which could be considered to be a trimline, to the Little Ice Age.

Figure 3 – The main groups of trimline terms from Table 1 are graphed according to the decade of publication of the studies using these terms, clearly showing both an increase in the popularity of trimlines research as well as an increase in the diversity of different types of terms used to describe trimline features. This has led to an increasingly confusing literature with a terminology that is difficult to use consistently.

Figure 4 – Thorp's method for identifying trimlines relies on mapping zones of glacial erosion and contrasting zones of frost weathering and periglacial slope processes. He found that clear trimline features were visible on spurs in his study

area but that the boundary between the two landsurface zones was more diffuse on the majority of valley slopes. Therefore, he used aerial imagery and fieldwork to map the lower limit of frost weathering and the upper limit of glacial erosion, giving an upper and lower bound for the trimline location. a) This schematic diagram illustrates the key features that Thorp used to identify the two landsurface zones and the dotted lines represent the upper and lower bounds of trimline elevation (reproduced from Thorp 1981). b) Once the upper and lower bounds had been identified, Thorp was able to calculate the mean elevation of the trimline on each mountain or spur. By comparing mean trimline elevations between mountains, he was able to draw in the mean trimline and determine the morphology of the former ice surface as well as the ice thickness (reproduced with permission from Thorp 1986).

Figure 5 – Two possible explanations for British-Irish Ice Sheet trimlines were tested via the application of cosmogenic nuclide dating: (a) that the glacial trimlines represent the upper limit of glaciation during the LGM, i.e. the trimlines were formed at the ice margin; (b) that the glacial trimlines represent an englacial thermal boundary between warm-based, flowing and erosive ice in the valleys and cold-based static ice on the mountain tops, which preserved the frost weathering regolith from preceding interglacials. Research in Britain and Scandinavia using cosmogenic nuclide dating eventually found that both of these scenarios are possible, meaning that trimlines cannot be assumed to be ice marginal without further supporting evidence.

Figure 6 – This schematic illustrates the trimlines and other features in two adjacent valleys. Some trimlines are clearly linked to the modern glaciers, showing patterns of historic recession and linking to recent moraines. These historic trimlines can be used to produce 3D palaeoglacial reconstructions and to estimate rates of glacier thinning or ice volume loss. Other trimlines, more distant from glaciers or in places that no longer contain glaciers often record much larger ice masses. These older Quaternary trimlines are typically less clearly expressed than the historic trimlines and when pieced together they reveal useful information of on former ice cap or ice sheet extents and thicknesses, points of confluence between different valleys' ice flows and the identification of palaeo nunataks. Quaternary trimlines may also indicate the position of thermal boundaries at the bed of palaeo ice sheets.

Figure 7 – The distribution of trimline research, with Quaternary studies in red and historic in blue. The size of the circles relates to the percentage of published studies located in each area. The global distribution of Quaternary (a) and historic (b) studies show that trimlines can be found in a wide range of glacial environments and are not limited to specific glaciological, climatic or geological conditions. It is also clear that trimline research has been highly clustered, with higher densities in North America (c) and Europe (d) than other locations, likely to be a bias towards locations that are easily accessible and generally well-researched. The regional distribution of trimline research in North America (c) shows a clustering around mountainous areas of on-going glaciation or at the fringes of the former Laurentide and Cordilleran Ice Sheets. In Europe (d) research has similarly been focused in rugged topography but trimlines have also been found in the central areas of former ice sheets, for example associated with the Fennoscandian Ice Sheet in Northern

Sweden and Northern Norway. However there has been relatively little research into historic trimlines in Europe, despite clearly visible Little Ice Age trimlines associated with many glaciers in Scandinavia and the Alps (e.g. Figure 1). (Background map from Wikipedia Commons. File name: BlankMap-World6.svg)

Figure 8 – Geomorphological map of trimlines (red) in central western Spitsbergen, Svalbard and their parent existing ice masses (blue), from Rootes (2018). The position and shape of individual trimlines are shown in full detail, aiding visual identification of possibly synchronous trimlines on opposite sides of a glacier, sequences of trimlines that indicate downwasting (e.g. in the forefield of Bullbreen), possible palaeo glacier confluences, and trimlines that are not linked to any modern glacier. This wealth of information is not obvious in maps that just mark trimlines as a single point/symbol.

Figure 9 – Suggested decision tree for glacial trimline terminology. When a linear feature on the slopes of a glacierised or formerly glaciated valley is identified it is termed an ‘apparent trimline’, which is a purely descriptive term. The initial interpretation of the feature ascertains whether it is of glacial origin or not. If it is found to be glacial then it is termed a ‘glacial trimline’ and can be classified according to its expression (Figure 10a). Further analysis of the trimline’s expression, morphology, preservation, location and age, if known, may allow the formation of the trimline to be determined as either ice marginal or thermal.

Figure 10 – a) Observable means of trimline expression as documented in the literature and from investigation of Svalbard trimlines in Rootes (2018), including associated ice marginal features that are often used in conjunction with glacial trimlines. The suggested categorisation and terminology that has undergone initial testing in central western Spitsbergen (Rootes 2018; Chapter 4) but requires further application to a wider range of glacial environments. Figures 9b)-9f) show some examples the different modes of trimline expression. b) A trimline (white dashed line) expressed by a discontinuity in a slope landforms or processes, in this case depositional talus cones and erosional gullies above Conwaybreen in Svalbard (TopoSvalbard; imagery from Norwegian Polar Institute). In this example the trimline is also expressed as the limit of glacially deposited drift. c) A series of a lateral moraine trimlines (white dashed lines) on the Pasu Glacier in the Karakorum (Google Earth; imagery from Landsat). d) An example of an erosional imprint limit in the Grimsel Pass area, European Alps (Kelly *et al.* 2004). e) An example of a truncated spur, marked with an arrow, near the snout of Nigardsbreen, Norway (C.M. Rootes June 2011). f) A vegetation trimline associated with an unnamed glacier flowing down from Icemaker Mountain in British Columbia, Canada (Google Earth; imagery from Landsat).

Figure 11 – These images contain examples of previously unrecognised trimlines (marked by red arrows) that are not known to have been included in any published study. a) and b) are trimlines associated with the debris-covered Pasu glacier in the Karakorum, Pakistan. The trimline in a) appears to be a surface aging contrast,

marked by a distinction in the vegetation cover, whilst b) could be a contrast in glacier deposition, with some sections that appear to be lateral moraines, but could also be an erosional step. In c) an unnamed glacier in Alaska (Lat. 57.6224° Long. -132.9562°) has a surface aging/erosional contrast trimline along the main trunk glacier, with a nearby smaller glacier's former ice margin marked by an almost continuous surface aging trimline (red dotted line). d) shows a clear lateral moraine trimline along the side of the Tasman Glacier, New Zealand. There is also a smaller surface aging/ erosional contrast on the opposite side of the glacier. Like the Pasu glacier (a and b), the Tasman glacier (d) is debris-covered and the glacial trimlines of this type of glacier have received little or no detailed study in the literature to date. All images from Google Earth and sourced from: a) Landsat/ Copernicus ©CNES/ Airbus; b) Landsat/ Copernicus ©CNES/ Airbus and ©DigitalGlobe; c) ©DigitalGlobe; d) Landsat/ Copernicus ©CNES/ Airbus and ©DigitalGlobe.