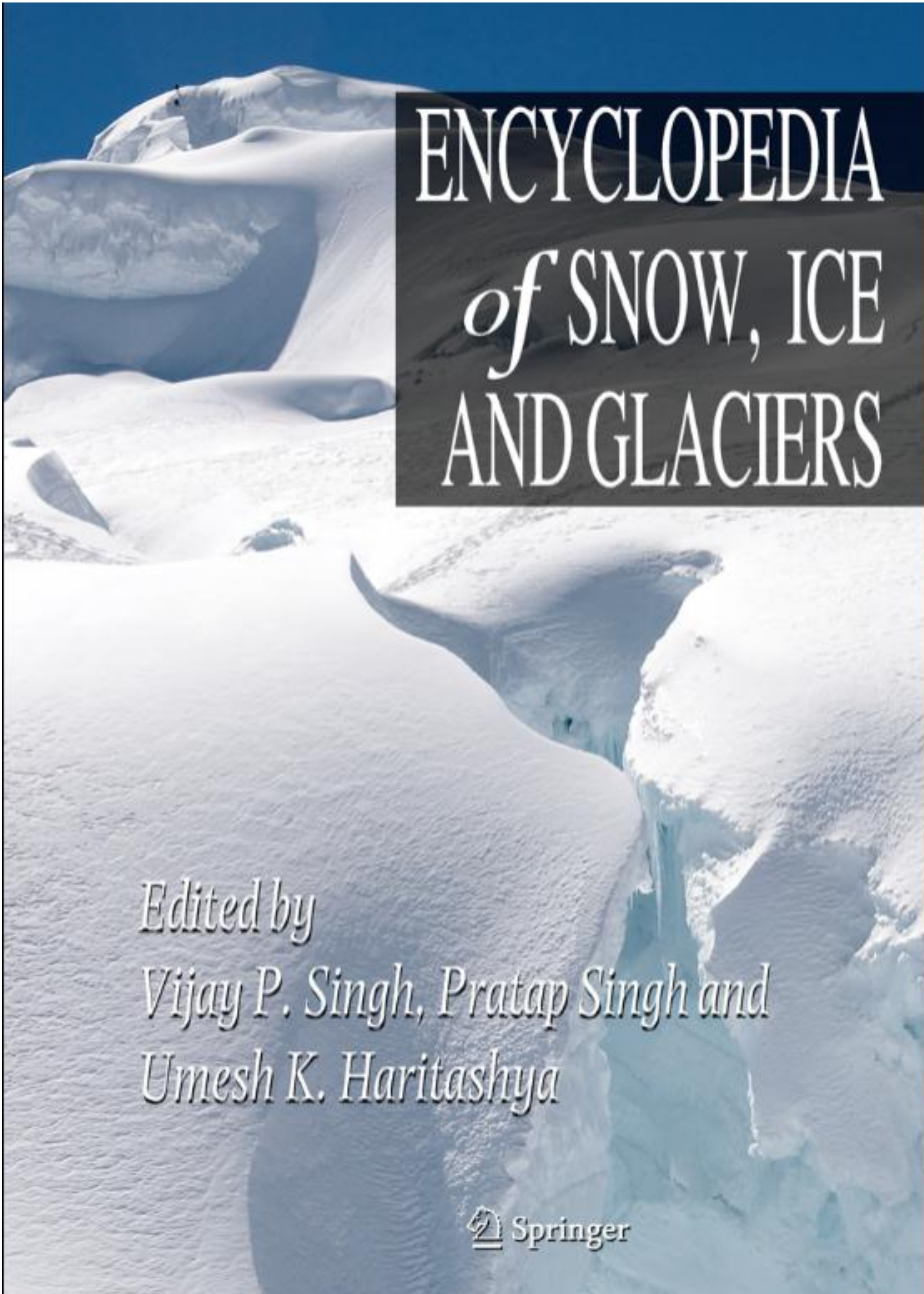

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TREE-RING INDICATORS OF GLACIER FLUCTUATIONS

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Definition

Glacier response to climate change is commonly benchmarked by dating trees overrun and killed during glacial advances (Figures 1 and 2), or by dating trees found growing on moraines formed as glaciers retreat from advanced positions. These traditional dendroglaciologic applications employ dendrochronologic methods to reconstruct past glacier activity. Evolving methodologies, including the construction of proxy glacier mass balance histories from tree rings, are expanding the avenues of glaciological research by using tree-ring indicators to examine the pre-instrumental response of glaciers to changing climates.

Dendroglaciology

Dendroglaciology describes the application of tree-ring dating principles to assign ages to glacial sediments and landforms (Schweingruber, 1988; Luckman, 1998; Smith and Lewis, 2007). Lawrence (1946) pioneered early efforts and numerous researchers subsequently used the total number of annual rings within first-colonizing trees inhabiting deglaciated terrain as a minimum estimate of surface age (McCarthy and Luckman, 1993; Osborn et al., 2007; Koch, 2009). Surveys of the age of the oldest trees colonizing recently deposited moraines provide the chronological control necessary to develop detailed Little Ice Age glacial histories (Heusser, 1956; Smith et al., 1995; Luckman, 2000; Allen and Smith, 2007).

In many settings, retreating glaciers regularly expose the remains of forests buried or killed by past advances (Figures 1 and 2). Dendroglaciology allows for dating the glacier activity recorded by these woody deposits (Luckman, 1993, 1998). This approach to event dating rests foremost on the assumption that trees in the higher latitudes form annual growth rings; and, secondly that the annual tree ring-width vary in response to limiting factors (i.e., temperature and/or precipitation climate) to create distinctive time series (Fritts, 1976).

Tree-ring cross-dates of living and glacially killed trees provide an opportunity to precisely date glacial forefield histories by

- Resolving the year of death of glacially overridden trees by cross-dating, a process that involves comparing ring-width patterns, between living and glacially reworked trees (Osborn et al., 2001; Reyes et al., 2006; Jackson et al., 2008; Barclay et al., 2009a, b).
- Establishing the calendar year of glacial advance into ice-marginal forests, through the selection of trees exhibiting callous tissue, corrasion scars, or reaction wood, which demonstrate abnormal cell development in response to encroaching glacier snouts (Luckman, 1988; Wiles et al., 1996).
- Applying radiometric dating to the perimeter wood of subfossilized samples, when ring-widths fail to cross-date with a master chronology, or when the preservation of wood is poor (Glasser et al., 2002; Wood and Smith, 2004; Allen and Smith, 2007; Barclay et al., 2009a, b).

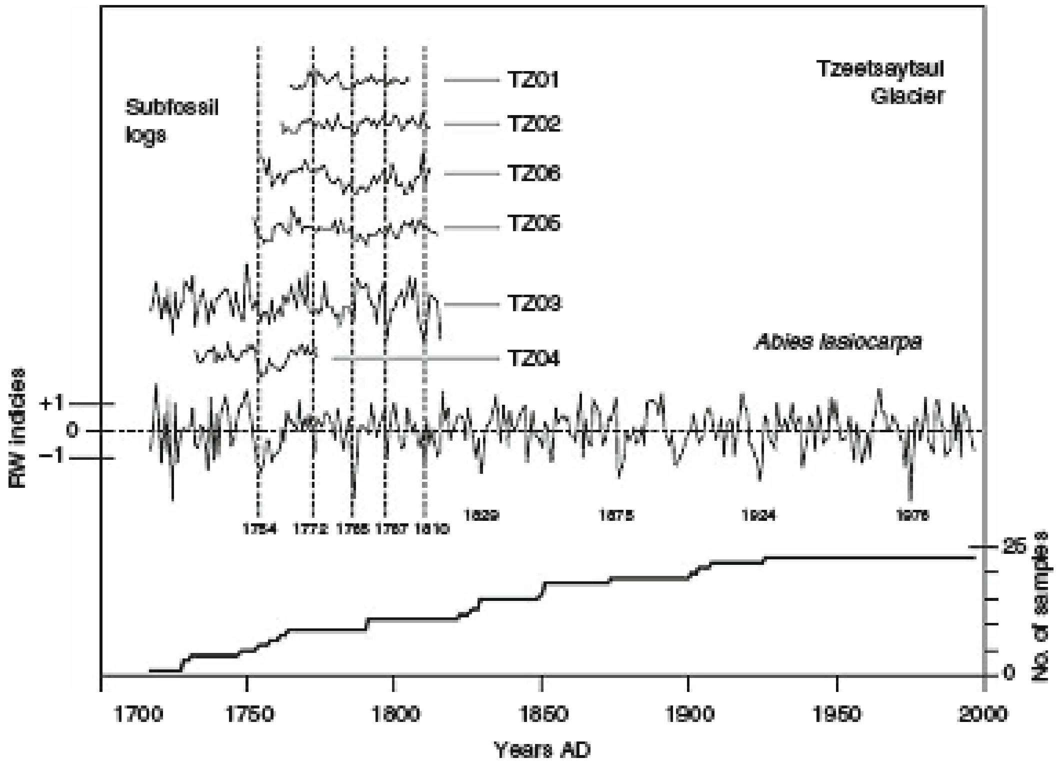
Tree-Ring Indicators of Glacier Fluctuations, Figure 1 The construction of a Little Ice Age lateral moraine in the British Columbia Coast Mountains killed and buried this 232-year-old subalpine fir tree in 1733 AD.

Tree-Ring Indicators of Glacier Fluctuations, Figure 2 Standing snag located adjacent to the distal slope of Little Ice Age lateral moraine in the British Columbia Coast Mountains. The tree died in 1738 AD, following the deposition of the moraine. Note in the background the growth of subalpine fir trees on the stabilized moraine surface. Counts of the number of annual rings in the oldest cohort of living trees provide a minimum date for surface stabilization following the most recent advance of glacial ice.

Tree-Ring Indicators of Glacier Fluctuations, Figure 3 Excavation of subfossil trees killed and buried in till by an advancing glacier in the British Columbia Coast Mountains. Cross-dates of the annual ring patterns within the trees to a living tree-ring chronology indicate the subfossil boles and branches were entombed in 1815.

- Relating the ring-width patterns of ice marginal trees to glacier-climate fluctuations and moraine building episodes (Bray and Struik, 1963; Matthews, 1977; Pederson et al., 2004; Pelfini et al., 2005; Nesje et al., 2008).

The global recession of glaciers over the last century has led to the exposure of an abundance of cross-datable material (Figure 3). These subfossil remains have successfully been interpreted using dendroglaciology to detail ice front fluctuations (Smith and Desloges, 2000). The annual ring-width patterns of the subfossil wood is measured and compared to the radial growth trends of living tree–ring chronologies (Figure 4). Where the growth trends match over time and cross-date, the perimeter date of the subfossil samples is interpreted to indicate when the glacier was advancing and killing the trees.



Tree-Ring Indicators of Glacier Fluctuations, Figure 4 Summary of dendroglaciological studies used to date subfossil wood shown in Figure 3. The upper portion of the figure illustrates the duration of cross-dated subfossil samples. While the youngest portion of each record indicates the pith date of the sample, the oldest portion does not necessarily represent the absolute age of the sampled wood due to surface abrasion. The middle portion of the figure illustrates the annual growth trends found in living trees growing in the forest adjacent to the glacier. Dates refer to common pointer years in the chronology and within the subfossil samples. The lower portion of the graph shows the sample depth of the living chronology (from Smith and Desloges, 2000).

Although dendroglaciology benefits from simplicity and low cost, several limitations are worth noting. The success of dendroglaciological research depends upon an abundant supply of wood and subsequent preservation within actively eroding proglacial environments (Allen and Smith, 2007; Koch, 2009). Dendroglaciologic interpretations are also restricted in their temporal range. For example, the success of cross-dating depends upon the longevity of local trees, which often fail to exceed 300–400 years in many subalpine locations (Schweingruber, 1988). Nonetheless, millennial length chronologies are being compiled from subfossil wood that has been preserved in glacial and glaciofluvial sediments that allow for absolute dating of glacier fluctuations over extended time periods (Scuderi, 1987; Barclay et al., 1999, 2009a).

Limitations to dendroglaciological dating arise because: (a) intercepting the pith when coring a tree is rare, especially for large diameter trees (Villalba and Veblen, 1997); (b) extracting cores from the root ball is challenging (McCarthy et al., 1991; Winchester and Harrison, 2000); (c) tree-ring series sometimes contain missing and/or false ring boundaries, resulting in incorrect age determinations; and, most importantly (d) opportunities for determining locally relevant ecesis intervals, the time it takes for seedlings to establish, are often limited by the lack of reliable control surfaces and/or inconsistent colonization rates due to microclimatic effects (Sigafoos and Hendricks, 1969; Villalba et al., 1990; McCarthy and Luckman, 1993; Koch, 2009).

Dendroclimatic mass balance reconstruction

Dendroclimatic investigations focused on climate-sensitive tree species found in glaciated settings offer the opportunity to acquire insights into glacial mass balance changes at decade-to-century timescales. A growing number of studies have demonstrated that a strong relationship exists between the annual ring-width variations of some tree species and glacier ice front fluctuations (Bräuning, 2006; Yang et al., 2008; Borgaonkar et al., 2009). The underlying relationship to climate variability has allowed for the hindcasting of mass balance fluctuations.

Changes in glacier volume reflect the sensitivity of glaciers to changes in climate. Conventional mass balance surveys provide a way to evaluate the long-term impact of climate variability on changes in glacier volume, area, and length (Calmanti et al., 2007). Most mass balance records are sparse and of short duration. Following recognition that the annual radial growth variations of trees are often significantly correlated to local glacier activity (LaMarche and Fritts, 1971; Yang et al., 2008; Borgaonkar et al., 2009), attention has been directed to developing extended proxy glacier activity records from tree rings.

When examined in detail, mass balance measurements reveal that the winter and summer seasons are marked by peak accumulation and peak ablation phases (Bitz and Battisti, 1999). The same seasonal climates that govern these glaciological relationships influence the growth of tree rings. Climate conditions that promote above-average radial growth (wide rings) are the same conditions that favor glacier ablation (negative mass balance) and retreat (Bray and Struik, 1963; Bräuning, 2006). Conversely, the conditions that result in a shortened growing season and below-average radial growth trees (narrow rings) lead to accumulation, positive mass balance conditions, and glacier advance (Watson and Luckman, 2004; Larocque and Smith, 2005; Calmanti et al., 2007). Recognition of the inverse climatic relationship between tree-ring growth and glacier mass balances indicates it is possible to estimate past mass balance variations from tree-ring data (Leonelli et al., 2008).

A number of different methodological approaches and tree species have been used to explore the potential for reconstructing local and regional mass balance records (Lewis and Smith, 2004; Watson and Luckman, 2004; Larocque and Smith, 2005; Calmanti et al., 2007; Linderholm et al., 2007; Leonelli et al., 2008). Despite their inherent uncertainties, most tree-ring-derived mass balance models appear to provide a good approximation of summer (B_s) and net (B_n) mass balance conditions. Less certain is their ability to fully represent glacier winter balance (B_w) (Linderholm et al., 2007).

As noted by Leonelli et al. (2008), limitations to reconstructing glacier mass balance histories from tree ring chronologies arise because their annual variations are affected by distinct biological and physical processes and because diverse climatic factors may influence them during different periods of the year. It is also likely that the mass balance response of contemporary glaciers to climate is distinct from that of larger Little Ice Age glaciers (i.e., Nesje et al., 2008). If this is the case, mass balance models based upon assumed present-day causal relationships to climate by glaciers and tree growth may bias the reconstructions.

Summary

Dendroglaciological research methodologies provide the evidence necessary to precisely date the glacier activity. Annual ring counts of trees colonizing recently deglaciated terrain provides a spatial record of the glacial retreat patterns, as well as the means to establish chronologies of recent lateral and terminal moraine stabilization.

Dendroglaciologic evidence exposed by retreating glaciers provides an opportunity to develop Holocene glacial records. Since Holocene ice fronts periodically extended below tree line in many regions, advancing and retreating glaciers repeatedly overrode and buried forests beneath till deposits. Cross-dating and radiometric dating of these subfossil deposits provides an opportunity to delineate ice front positions over several millennia.

Tree-growth patterns have been used to reconstruct glacier behavior and mass balance with encouraging results. The extension of current glacier mass balance measurements to several centuries enables a more precise assessment of the impact of past climates on glacial systems.

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Cross-references

Climate Change and Glaciers
Dating Glacial Landforms
Glacier Mass Balance
Holocene Glacier Fluctuations
Little Ice Age