Quaternary Research 71 (2009) 22–26

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Short Paper

Tree-ring crossdates for a First Millennium AD advance of Tebenkof Glacier, southern Alaska

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ARTICLE INFO

Article history:
Received 14 March 2008
Available online 12 November 2008

Keywords:
Tebenkof Glacier
Alaska
First Millennium AD
Little Ice Age
Holocene climate
Tree rings
Dendrochronology
Glacier fluctuation

ABSTRACT

Tree-ring crossdates from glacially killed logs show that Tebenkof Glacier advanced into a forefield forest in the AD 710s and 720s. Recession from this First Millennium AD (FMA) advance occurred before the 950s, after which the ice margin readvanced in the 1280s to 1320s at the start of the Little Ice Age (LIA). A more extensive LIA advance was underway from the 1640s to 1670s, and the terminus stayed at or near its LIA maximum until the 1890s. These are the first absolute tree-ring crossdates for a FMA glacier advance in North America and support growing evidence from northwestern North America and Europe for a significant cool interval in the centuries around AD 500.

Introduction

Tree-ring crossdates of glacially killed logs have provided a precisely dated and detailed picture of Little Ice Age (LIA) glacier fluctuations in southern Alaska. Hundreds of logs have been recovered and crossdated from forefields along ~500 km of the northern Gulf of Alaska coastline (e.g. Wiles et al., 1999, 2008; Barclay et al., 2003). Collectively these data show that land-based ice margins were advancing between the AD 1180s and 1300s in the early LIA; more extensive advances were underway between 1600s and 1715, and a late phase of advance culminated between the 1880s and ~1900.

In this paper we extend these tree-ring-dated forefield histories back into the First Millennium AD (FMA). Previous work in 1992 at Tebenkof Glacier identified logs that had been killed by a pre-LIA advance (Wiles et al., 1999); here we integrate new collections made in 1999 with these older data and provide new absolute tree-ring crossdates for the complete LIA and FMA data set from Tebenkof. Although FMA ice advances in the region have previously been constrained with radiocarbon ages (e.g. Reyes et al., 2006), these crossdates from Tebenkof Glacier are the first calendar dates that we are aware of for the FMA ice expansion in North America.

Background

Tebenkof Glacier is located in the northern Kenai Mountains on the western edge of Prince William Sound (Fig. 1). It is an approximately 12.5 km-long valley glacier that originates among peaks of just over 1000 m, and flows northeast to terminate at the southern entrance of Blackstone Bay. A terminal moraine complex and vegetational and erosional trimlines define the Holocene forefield that has been exposed by ice margin retreat over the past century (Fig. 1). Deposits of till and outwash mantle much of the forefield and are interspersed with bedrock knolls that rise tens of meters above the general land surface. Meteoric and glacial meltwater streams have dissected the till and outwash deposits and water is often ponded against sections of the ice margin; however, the terminus does not calve icebergs and so the current ice-contact lakes are probably not very deep.

Climate is maritime with mean temperatures of −2.7°C in January, 13.9°C in July, and average annual total precipitation of 4705 mm (NCDC normals, 1971–2000) recorded at the town of Whittier, 15 km to the west. Mountain hemlock [*Tsuga mertensiana* (Bong.) Carr] dominates the forests around the Tebenkof forefield and forms almost pure stands down to sea level. Willow and alder are the first woody species to recolonize deglaciated areas, and are succeeded by mountain hemlock with occasional Sitka spruce [*Picea sitchensis* (Bong.) Carr].

The first detailed observations of the Tebenkof terminus were made in 1909 and 1910 (Grant and Higgins, 1913; Tarr and Martin, 1914), and glacially killed logs being revealed by the retreating ice margin were noted in 1935 (Field, 1937; Cooper, 1942). Minimum age

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doi:10.1016/j.yqres.2008.09.005

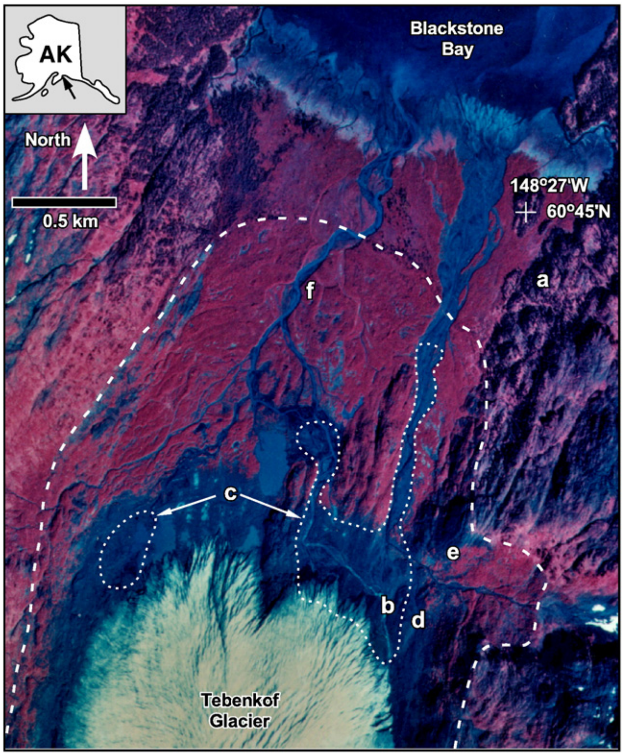

Figure 1. False-color aerial photograph of the Tebenkof forefield. Dashed line marks Little Ice Age maximum position; letters and dotted areas are sample locations. Photograph taken August 12, 1984.

estimates for the terminal moraine and adjacent outwash based on ring counts of first-generation trees were made by Tarr and Martin (1914), Vierek (1967), Crossen (1997) and Wiles et al. (1999). Crossen (1997) and Wiles et al. (1999) reported radiocarbon ages from logs on the forefield, and the latter and Barclay et al. (1999) included logs from Tebenkof in a composite tree-ring chronology for western Prince William Sound that spanned AD 873 to 1991. However, an additional floating tree-ring chronology of seven logs reported by Wiles et al. (1999) was only dated to the FMA by a single radiocarbon age.

Methods

Fieldwork in 1999 focused on collecting increment cores and slabs from logs on the eastern side of the forefield (Fig. 1). Samples were taken from trunk sections with the best-preserved outer rings and from within a few meters of the roots whenever possible. Logs sampled in 1992 were re-examined but not re-sampled, and during data analysis the ring-width series collected in 1992 and 1999 were compared to ensure that no individual log on the forefield was inadvertently duplicated in the final data set.

Tree-ring widths were measured to the nearest micron and crossdating used to aggregate samples into floating chronologies. Crossdates were initially developed using the COFECHA program (Holmes, 1983; Grissino-Mayer, 2001) and then verified graphically (Pilcher, 1989). The resulting floating chronologies, composed of both 1992 and 1999 samples, were then assigned calendar dates by crossdating with 1) living trees growing beyond the terminal moraine in the Tebenkof valley (Fig. 1, location a), 2) the Nellie Juan master chronology (AD 1069–1999) from 30 km to the south (Barclay et al., 2003), and 3) the Columbia master chronology (AD 583–2002) from 90 km to the northeast (Wilson et al., 2007; Wiles, unpublished data). Radiocarbon ages provide general support for the final crossdates; samples were calibrated in CALIB 5.1 (Stuiver and Reimer, 1993) using the IntCal04 calibration curve (Reimer et al., 2004), and central-point age estimates derived as the weighted average of the probability distribution function (Telford et al., 2004).

Minimum age estimates for ice retreat were based on annual ring counts in cores of living trees growing on glacigenic deposits. Different workers at Tebenkof have used different ecesis times in previous studies, with estimates for this elapsed time between substrate stabilization and germination and survival of spruce and hemlock seedlings varying from 25 yr (Crossen, 1997) to 20 yr (Vierek, 1967) to 15 yr (Wiles et al., 1999). We use an ecesis interval of 15 yr in this paper because the Wiles et al. (1999) estimate was based in part on data

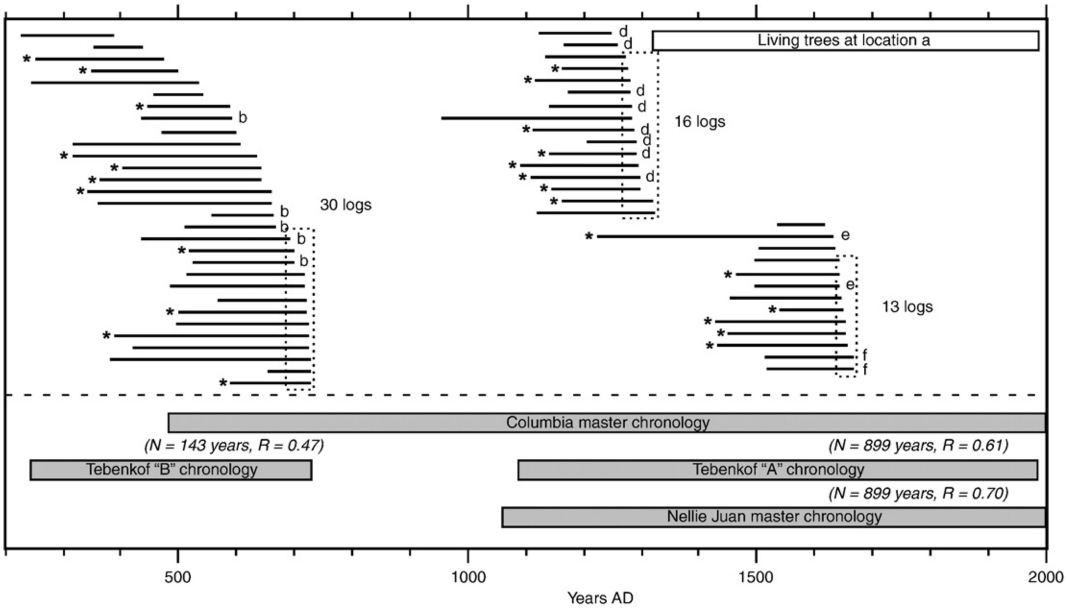

Figure 2. Age spans of crossdated samples. Upper panel: horizontal block shows the composite age span of living trees included in the Tebenkof "A" chronology and horizontal lines show growth intervals of individual logs. Star symbols indicate samples that included pith, letter labels indicate sample locations b, d, e or f for logs *in situ* or in original glacigenic deposits, and dotted boxes show inferred intervals when the ice margin was advancing and killing trees. Lower panel: blocks represent age spans of the four tree-ring-width chronologies used in this study, and numbers in parentheses are years of overlap and correlation coefficients between the Tebenkof chronologies and the respective master chronologies. The Tebenkof chronologies are truncated when sample size is less than two trees and so are shorter than the total duration of forest growth shown by the individual log bars.

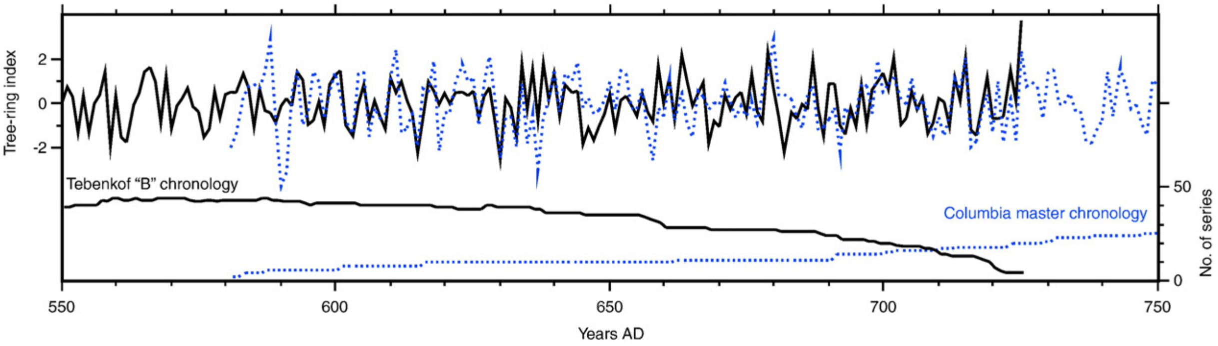

Figure 3. Crossdate of Tebenkof "B" chronology (black solid lines) with Columbia master chronology (blue dotted lines). Upper plot shows tree-ring-width indices from COFECHA, which were averaged from series that were standardized using 32-yr splines and had persistence removed to emphasize the high-frequency signal on which crossdating is based. Lower plot shows sample sizes of the two chronologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

collected at the terminus of Taylor Glacier, at sea level just 20 km south of the Tebenkof forefield in a similar maritime climatic setting.

Results

Tree-ring crossdates

A total of 59 logs were crossdated to form two final chronologies from the Tebenkof forefield (Fig. 2). The Tebenkof "A" chronology is composed of ring-width series from living mountain hemlock at location a (Fig. 1) together with two distinct age groups of logs; correlations of the total overlap with the Nellie Juan ($R=0.70$) and Columbia ($R=0.61$) master chronologies are significant at well above the 99% confidence level (CL). The Tebenkof "B" chronology overlaps in time with just the Columbia chronology (Fig. 3) with which it correlates ($R=0.47$) at above the 99% CL.

Statistical strength of the final crossdates was also assessed using correlations between the Tebenkof and master chronologies in 50-yr moving windows. Correlations in these windows only dropped below the 99% CL in two intervals, centered respectively at around AD 1160 and 1330; both cases were with the Tebenkof "A" to Columbia comparison, at no time was the correlation below the 95% CL, and graphical examination of the data found no crossdating errors. Correlations in the 50-yr windows between the Tebenkof "A" chronology and the Nellie Juan master chronology remained above the 99% CL throughout the period of overlap.

The radiocarbon ages (Table 1) provide further support for these crossdates. Sample β-93991 was cut in the laboratory as a block of 35 rings that crossdated to AD 539 to 573, and returned a radiocarbon age of 430 to 670 cal yr AD (2σ range). Sample β-55627 had a radiocarbon age of 1300 to 1630 cal yr AD (2σ range) and was cut in the field (~10 rings) from the outer edge of a log whose crossdated full span of growth was AD 1226 to 1634. The three other radiocarbon ages from logs (Table 1) cannot be linked to specific tree-ring samples, but are consistent with the crossdated age assignments for forest growth on the Tebenkof forefield.

First Millennium AD (FMA) ice advance

The oldest age group of 30 crossdated samples collectively shows that forest was established on the Tebenkof forefield by the AD 220s and that tree growth continued for the following 500 yr (Fig. 2). Five logs at location b (Fig. 1) appear to be *in situ* and require the ice margin to have been up-valley of this site until after AD 697. Other logs in this oldest age group had been transported from their original growth positions and were found in outwash and till deposits and modern meltwater channels across a broad area of the forefield (Fig. 1, area c). None had bark or pristine outer rings; however, the clustering of many of the last years of recorded growth in the 710s and 720s suggests that this was when the Tebenkof ice margin (Fig. 4) reached into and killed much of this forefield forest.

The maximum stand of this First Millennium AD (FMA) advance is not delimited by an extant moraine and so it must have been less extensive than the subsequent Little Ice Age (LIA) expansion. Retreat from the FMA maximum was underway before AD 956 when trees were recolonizing the Tebenkof forefield (Figs. 2 and 4).

Little Ice Age (LIA) ice advance

The second age group of 16 logs (Fig. 2) record advance of Tebenkof Glacier at the start of the Little Ice Age (LIA). Most of these logs had outer rings dates from the 1280s to 1320s and were found in or near a boulder deposit at location d (Fig. 1). This deposit may be an eroded remnant of a moraine deposited near the valley side during the

Table 1
Radiocarbon ages from the Tebenkof forefield

Laboratory number	Uncalibrated age (^{14}C yr BP)	Calibrated age[a]		Notes
		2σ range[b] (cal yr AD)	Weighted average[c] (cal yr AD)	
β-55627	490 ± 70	1300–1630	1430	~10 outer rings of log pushed into bedrock at location e. Full age span of log crossdated as AD 1226–1634. Wiles et al. (1999).
QL-4343	780 ± 20	1220–1270	1250	Log at southern end of bedrock knoll ~400 m north of location b. Crossen (1997).
UW-520	845 ± 70	1040–1280	1180	Log on outwash. Post, A., personal communication, 1993.
β-93991	1460 ± 70	430–670	590	35 rings crossdated as AD 539–573 from log in till ~50 m west of location b. Wiles et al. (1999).
QL-4344	1680 ± 25	260–420	370	Log among *in situ* stumps in channel at or near location b. Crossen (1997).
QL-4342	4180 ± 30	BC 2890–2640	BC 2770	Basal peat from bog on island in bay ~1.5 km north of terminal moraine. Crossen (1997).

[a] Calibrated with IntCal04 calibration curve (Reimer et al., 2004).

[b] Range is first and last intercepts of 2σ range with calibration curve.

[c] Central point estimate is weighted average of probability distribution function (Telford et al., 2004).

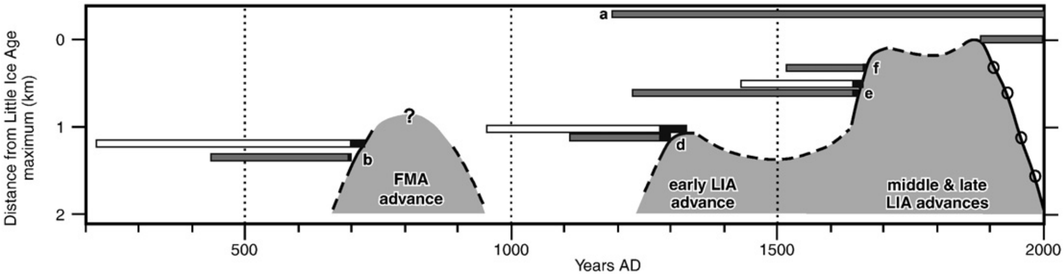

Figure 4. Time-distance diagram for Tebenkof Glacier terminus. Horizontal blocks show durations of forest growth based on tree-ring crossdates: grey blocks are for *in situ* logs and trees or logs in original glacigenic deposits, open blocks are for logs in modern stream channels or on the land surface, and black areas indicate inferred intervals when trees were being killed. Circles indicate ice margin positions based on direct observations and letters are sample locations shown in Figures 1 and 2 and described in the text.

maximum of this phase of advance; that the ice margin did not extend much farther down-valley at this time is shown by trees at location e that were alive throughout this interval (Fig. 4).

The most recent age group of 13 logs shows a more extensive phase of Little Ice Age advance (Fig. 2). Trees at location e (Fig. 1) were killed in the 1640s and 1650s, and the outermost rings of logs in till and outwash at location f (Fig. 1) record the terminus reaching close to its LIA maximum stand at *c*.1670 (Fig. 4). We infer that Tebenkof Glacier remained at or near this LIA maximum for the following 200 yr during which time the terminal moraine complex was constructed. An 803-yr-old (in 1992) living mountain hemlock at location a (Fig. 1) and a mid-Holocene radiocarbon age on basal peat from a bog on an island 1.5 km north of the terminal moraine (Table 1) show that this ice marginal position was not exceeded in the late Holocene.

Post-Little Ice Age (LIA) retreat

Trees growing on or adjacent to the terminal moraine have been used in four separate studies to date recession of Tebenkof Glacier (Table 2). Application of the same ecesis interval to these data shows that the results of these studies are consistent, with trees beginning to germinate on outwash near the terminal moraine in the 1880s and the outer ridges of the moraine stabilizing by 1891. Collectively these data suggest that retreat of the Tebenkof terminus was underway by the last decade of the 19th century.

Tarr and Martin (1914) reported that ice margin recession by 1910 amounted to 250 to 350 m. A further 300 m of retreat had occurred by 1935 and an additional 500 m by 1964 (Field, 1937, 1975). In 1984 the Tebenkof terminus was 1.6 km from its LIA maximum and this ice margin recession has continued into the 21st century.

Discussion and conclusions

Tree-ring crossdates show that Tebenkof Glacier advanced into a forefield forest in the AD 710s and 720s. Previous estimates of the date of this FMA expansion have been based on radiocarbon ages (Crossen, 1997; Wiles et al., 1999) and have suggested that this Tebenkof advance could have occurred several centuries earlier. Similarly, radiocarbon-based estimates for advances of Tebenkof Glacier in the LIA (Table 1) tend to be earlier than tree-ring crossdates of the same events. This type of discrepancy, which has been noted elsewhere in western North America (e.g. Luckman, 1994; Barclay et al., 2006), reflects the lower precision of radiocarbon ages and perhaps the inadvertent incorporation of older wood in radiocarbon samples, and should be considered when radiocarbon ages are the only method used to constrain glacier histories.

Radiocarbon ages show that at least 19 glaciers in the coastal mountains of western North America advanced in the centuries centered around 500 cal. AD (Reyes et al., 2006; Allen and Smith, 2007). Some of these FMA expansions were of similar extent to the later LIA advances and stratigraphically superposed forest horizons at Surprise Glacier in British Columbia suggest that the FMA may have included two distinct phases of advance (Jackson et al., 2008). Although the precision issues of radiocarbon ages limit the degree to which such records can be compared with absolute tree-ring-dated records (Baillie, 1991), the AD 710s to 720s advance of Tebenkof Glacier appears to correspond generally with the later part of the FMA interval. This is consistent with Tebenkof Glacier reaching its most recent maximum in the late 19th century in the last phase of the LIA.

Absolute tree-ring crossdates have been used to constrain FMA fluctuations of two glaciers in the European Alps (Holzhauser et al., 2005). Following a possible small advance in the AD 270s, a major advance of Great Aletsch Glacier was underway by the AD 430s and by the 590s the ice margin was within ~100 m of the subsequent LIA maximum. Lower Grindelwald Glacier was expanding and killing trees from AD 527 to 578 and then again from 820 to 834; however, the extent of its FMA advances is currently unknown. Together with radiocarbon ages of glacially overrun wood at other termini in the Alps (Holzhauser et al., 2005; Joerin et al., 2006), these records show that the FMA advance was not limited to western North America. Collectively the North American and European Alps glacier forefield records are consistent with temperature paleorecords from Alaskan lakes (Hu et al., 2001; Loso et al., 2006), dendroclimatic data from Scandinavia and Siberia (Briffa, 2000) and hemispheric and global multi-proxy reconstructions (Mann and Jones, 2003; Moberg et al., 2005) that all show significant cooling in the centuries around AD 500.

The synchrony of land-based glacier fluctuations during the last two millennia, while interesting from a climatic perspective, has been a problem for developing long tree-ring chronologies from glacier forefields in southern Alaska. When all termini are expanded there are no trees alive on forefields and so gaps occur in the composite ring-width chronologies. The key to solving this problem has been to develop tree-ring chronologies from the fjord margins of tidewater glacier systems; both the Nellie Juan and Columbia master chronologies are from such settings and these two records span the hiatuses

Table 2
Minimum age estimates from the terminal moraine

Tree species[a]	Year cored	Number of rings	Germination date[b]	Notes
Alder	1910	12	1898	Main moraine ridge on western forefield. Tarr and Martin (1914).
Willow	1910	18	1892	Outer moraine at west edge of forefield. Tarr and Martin (1914).
Sp. or He.	1957	52–62	1880–1890	Trees on outwash. Vierek (1967).
Spruce	1987	78[c]	1894	Main moraine ridge. Crossen (1997).
Sp. or He.	1992	86	1891	Outer moraine ridge on western forefield. Wiles et al. (1999).

[a] Sp.: spruce; He.: hemlock.
[b] Ecesis correction of 15 yr for spruce and hemlock, 0 yr for alder and willow.
[c] Includes height correction from Crossen (1997).

and sample size minima of collections from Tebenkof and other land-based glaciers. Tidewater glacier fluctuations are asynchronous with other termini because of factors such as iceberg-calving and fjord geometry, and the typically long interval between successive advances means that logs found in tidewater glacier deposits often have significantly more rings than those found on terrestrial forefields where terminus expansions have been more frequent. While these factors make the histories of tidewater glaciers unsuitable for interpretation as climate proxies, tree-ring collections from such glaciers are essential for the development of long tree-ring chronologies in the southern Alaskan region.

Acknowledgments

This work was supported by the National Science Foundation under Grants 9912124, 9910805 and 9905493. We thank Dino Maraldo and Jason Graves for assistance in the field and preliminary analysis of some of the tree-ring samples. Reviews by Brian Luckman, Kristine Crossen, Associate Editor Lewis Owen and Senior Editor Alan Gillespie helped improve the clarity of the manuscript.

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