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Little Ice Age subsidence and post Little Ice Age uplift at Juneau, Alaska, inferred from dendrochronology and geomorphology

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Abstract

Application of dendrochronology and geomorphology to a recently emerged coastal area near Juneau, Alaska, has documented a Little Ice Age (LIA) sea-level transgression to 6.2 m above current sea level. The rise in relative sea level is attributed to regional subsidence and appears to have stabilized by the mid 16th century, based on a sea-cliff eroded into late-Pleistocene glaciomarine sediments. Land began emerging between A.D. 1770 and 1790, coincident with retreat of regional glaciers from their LIA maximums. This emergence has continued since then, paralleling regional glacier retreat. Total Juneau uplift since the late 18th century is estimated to be 3.2 m. The rate of downward colonization of newly emergent coastline by Sitka spruce during the 20th century closely parallels the rate of sea-level fall documented by analysis of local tide-gauge records (1.3 cm/yr). Regional and Glacier Bay LIA loading and unloading are inferred to be the primary mechanisms driving subsidence and uplift in the Juneau area. Climate change rather then regional tectonics has forced relative sea-level change over the last several hundred years.

Keywords: Uplift; Glacier rebound; Tectonics; Sea-level transgression; Little Ice Age; Dendrochronology; Geomorphology; Sitka spruce colonization

Introduction

The coastline at Juneau, Alaska, is currently emerging at a rate of 1.3 cm/yr (Savage and Plafker, 1991; Larsen et al., 2002). This emergence is part of a broad regional pattern of uplift in the northern part of southeast Alaska (NSEAK) centered in Glacier Bay, where rates of coastal emergence range up to 3.5 cm/yr (Fig. 1) (Hicks and Shofnos, 1965). These data on vertical motion in NSEAK, which rank among the highest in the world, were derived from analysis of a regional network of continuous and discontinuous tide-gauge measurements (Hicks and Shofnos, 1965; Larsen et al., 2003). More recently, GPS measurements with campaign-style precision have confirmed the rapid rates of uplift in this region (Larsen et al., 2001). However, the causes of this dramatic uplift, as well as its onset and history prior to tidal records, have remained in question. Hicks and Shofnos (1965) and later Clarke (1977) attributed NSEAK uplift to rebound from recent localized deglaciation or the combination of recent deglaciation and general post-last glacial maximum (LGM) deglaciation. However, some investigators have argued that part or all of the current regional uplift is tectonic in origin (Hudson et al., 1982; Horner, 1983, 1990; Barnes, 1990; Savage and Plafker, 1991).

Tidal records in southeastern Alaska extend back only a few decades. The prior history of the regional uplift has remained virtually unknown and is almost certainly important for deciphering the causes of current uplift. In this paper, I describe a methodology that has helped provide this history at Juneau, Alaska. The methodology involves the application of dendrochronology and terrace delineation and mapping to emergent coastal, forests. These analyses allowed determination of maximum sea-level transgression during the last several hundred years, subsequent onset of

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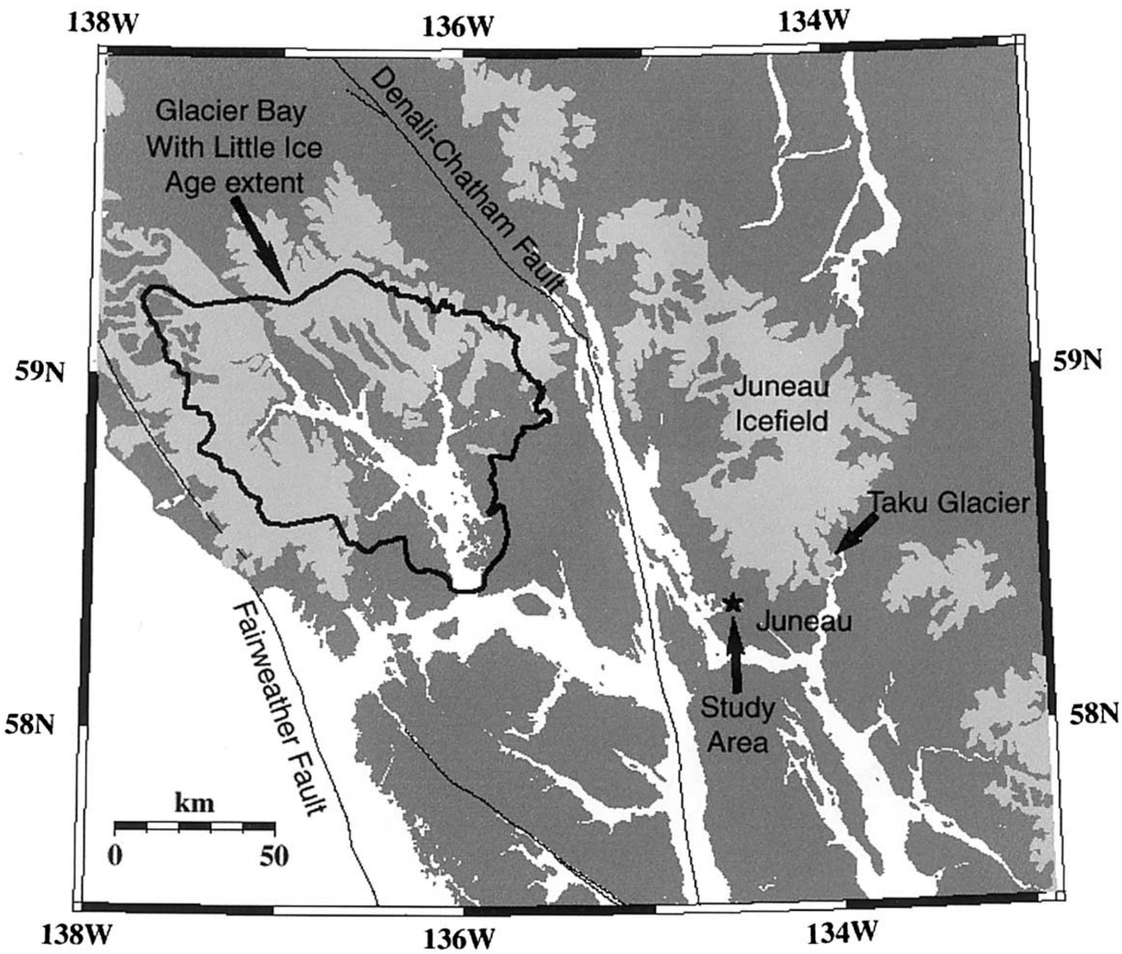

Fig. 1. Northern southeast Alaska showing major faults and ice fields. The seismically active, right-lateral strike-slip Fairweather Fault forms the boundary between the North Pacific and North American plates. The Juneau Ice Field mantles the Coast Mountains and lies north of the study area in Juneau. Outlet glaciers there have experienced substantial thinning and retreat since the Little Ice Age maximum in the mid 18th century. Tidewater calving retreats produced a substantially greater loss of ice in Glacier Bay during the same period.

coastal land emergence, and the total amount and trends of emergence since onset. Dendrochronology of coastal forests has been used to investigate residual isostatic rebound from the LGM at Hudson Bay (Bégin et al., 1993) and on the Baltic coastline (Cramer, 1985). Dendrochronology and geomorphology have also been used to study episodic co-seismic and postseismic crustal movements along coastlines of Alaska and Washington (e.g., Yamaguchi et al., 1997; Atwater et al., 2001; Benson et al., 2001). The case study presented here is partly modeled upon these investigations and uses a systematic application of dendrochronology and geomorphology to examine subsidence and uplift associated with late-Holocene glaciations and tectonic activity. The Little Ice Age (LIA), which roughly spanned a period lasting from the mid 13th century to the late 19th century in this region, is of particular interest in this study. If the recent submergence and uplift documented in this work are shown to be driven by LIA loading and unloading, then climate changes rather then tectonic forces have primarily forced regional sea-level changes.

Study area

The author's observations at a number of coastal areas found that coastal forests in NSEAK systematically increase in age away from shoreline. These first-generation forests, consisting primarily of Sitka spruce (*Picea sitchensis* (Bong.) Carr) and Sitka alder (*Alnus viridis* (Vill.) Lam. and DC. ssp. *sinuata* (Regel) A. and D. Love) commonly end at the foot of a riser eroded from soft sediments, above which stands a terrace of old-growth forest dominated by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The Juneau area was chosen to test the methodology because sites there are easy to access, tidal records indicate a relatively rapid rate of land emergence (1.3 cm/yr), terrace-riser morphology is well-defined, and the local and regional LIA glacial histories are well-known (Goodwin, 1988; Motyka and Beget, 1996, and references therein). The local tide-gauge records, which extend back to A.D. 1911 (Hicks and Shofnos, 1965; Savage and Plafker, 1991; Larsen et al., 2003), provide an independent measure of land emergence over the last sev-

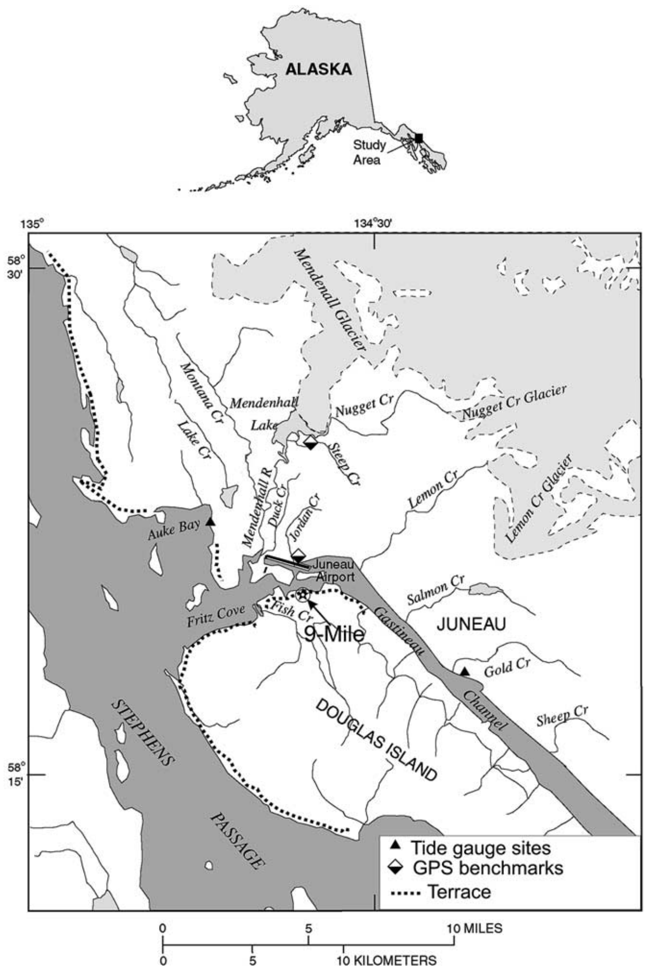

Fig. 2. Location of "9-Mile" field site for studies of coastal land emergence using dendrochronology and geomorphology. The NOS Juneau continuous reading tide gauge is located near Gold Creek on Gastineau Channel. Tide gauges have also been intermittently operated at Auke Bay. GPS uplift measurements with campaign-style precision have been conducted at two Juneau area benchmarks. Locations of some prominent exposures of terrace are shown by gray dotted line.

eral decades to which results from the dendrochronology study can be compared. Another independent measure of current local uplift comes from a series of precision GPS measurements made between 1992 and 2000 at nearby benchmarks (Larsen et al., 2001). The primary site of the investigation, called "9-Mile," borders the Mendenhall Wetlands Refuge on Gastineau Channel and lies directly across from Mendenhall Valley on Douglas Island (Fig. 2).

Methods

Background

Application of tree-ring analysis to determine the age of these coastal forests is relatively straightforward. Sitka spruce is the primary species used in this study because of its abundance, robustness, and relative ease of germination and because it and Sitka alder are usually the first tree species to colonize newly emerged coastal terrain in NSEAK. Sitka spruce can live for up to 600 years or more, and it is thus capable of dating events well back into the LIA, which in southeast Alaska lasted from about A.D. 1250 to 1900 (Goodwin, 1988; Motyka and Beget, 1996).

The date of germination of coastal trees can be determined from tree-ring analysis, providing an estimate for coastline emergence when the time lag between emergence and spruce germination ("ecesis") is taken into account. Thus sea-level transgression and onset of uplift can be dated. The amount of land emergence since germination can be determined by level-line surveys relative to tidewater (Cramer, 1985; Begin et al., 1993). The timing and scale of emergence can then be compared to regional glacial and tectonic histories. Despite its apparent simplicity, several factors affect the accuracy of dendrochronology for measuring uplift, including the dynamics of germination and tree succession along emerging tidelands (Bégin et al., 1993), corrections for tree age vs core height, and landscape corrections for elevation measurements. These uncertainties are described below.

Tree-ring dating

Descriptions of dendrochronology can be found in Schweingruber (1988) and Cook and Kairiukstis (1990). In this study, the largest and oldest appearing spruce trees along each elevation interval were cored with standard increment borers. Notes were taken on tree size, health, microterrain, germination substrate, depth of organic soil, and the height on the tree stem from which the core was extracted. Cores were mounted and sanded, and rings counted following standard procedures outlined in Stokes and Smiley (1968). Most cores were taken about a meter above ground surface.

Cores from two large spruce trees whose root systems straddle the riser were further analyzed for tree-ring width. The location and age of these trees suggested that they might have been impacted by rising sea level and/or by wave erosion. Ring widths were measured with an optical increnometer using standard procedures outlined in Stokes and Smiley (1968).

A correction for core height is required to estimate age of germination. This correction was determined by analyzing disks cut at ground level and at heights of 15, 50, and 100 cm above ground from pioneer and beach fringe spruce seedlings and saplings. A total of 24 trees were sampled. The average correction to age and the standard deviations are 2 ± 1, 6 ± 2, and 9 ± 3 years at heights of 15, 50, and 100 cm, respectively.

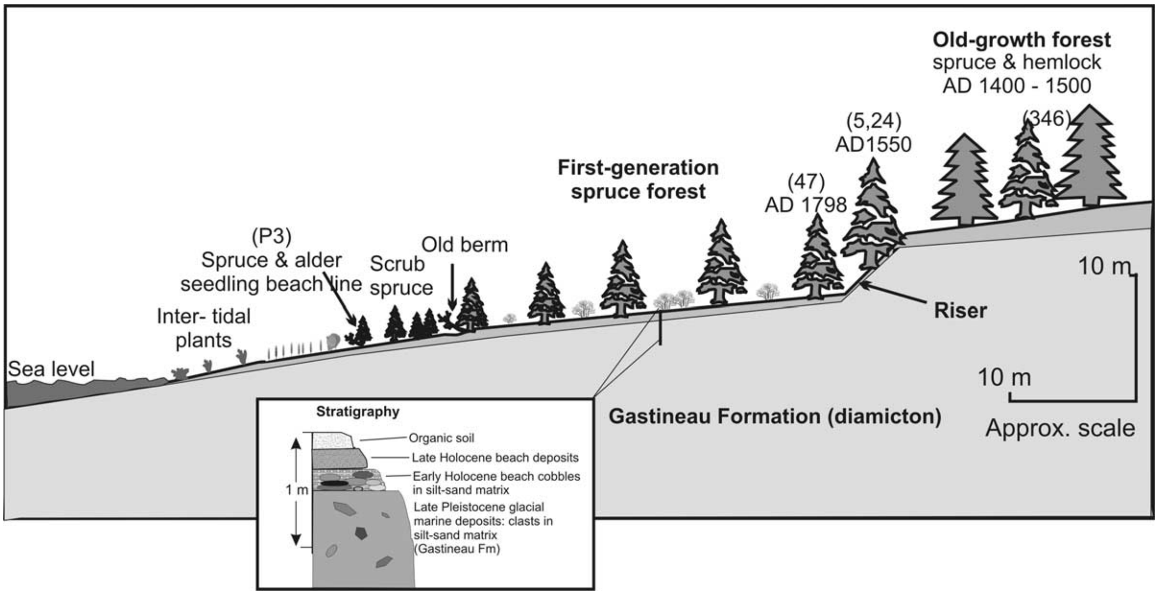

Fig. 3. Generalized profile of terrain and terrace–riser geomorphology at the 9-Mile field site. A first generation spruce forest increases in age from beach to a paleo-sea cliff eroded from a late-Pleistocene diamicton. An old-growth forest underlain by a thick layer of organic soil resides on the terrace above the riser. Inset shows general stratigraphy underlying emergent lower terrace.

Elevation

Standard level-line surveying techniques were used to measure ground elevations at the base of each tree with respect to a fixed reference mark set at higher high tide line on a specific day and tied to the National Ocean Service (NOS) Juneau tide gauge. Survey closures indicate that elevation measurements with respect to the reference mark are accurate to within ± 1 cm.

Various factors contribute to uncertainty in identifying the "germination surface" for a tree such as natural undulations, buttressing root systems, and germination substrata. A measure of the uncertainty in identifying the "ground surface" at the base of trees was obtained by repeat surveys of 40 trees at the study site by two independent teams. The majority of the surveys were within 20 cm of each other, but a few trees were as much as 50 cm different, mostly at higher elevations where ground disruption and root systems are more complex. The average of the two surveys was used for the ground surface elevation of trees that were surveyed twice and half the difference in surveys was taken as a conservative measure of uncertainty. The uncertainty in elevation of the remaining trees was taken to be half the average of the differences between the two surveys of the 40 trees: ± 13 cm.

Organic-rich soils accumulate as a result of forest litter and decay of organic material. Thus, the current ground surface may be several centimeters above the germination surface and accumulations will vary according to the time the terrain has been above sea level. To account for this the thickness of the organic-rich soil layer was measured near each tree using a soil auger. The thickness of the layer was subtracted from the measurement of the ground surface to obtain the germination surface. Uncertainties in soil thickness of ± 1 cm are added to the uncertainty in surveying to obtain total uncertainty.

Results and observations

Terrain description and geomorphology

Surface profiles were measured perpendicular to the shoreline along a traverse from the tidal zone to the upper terrace using standard level-line procedures and by taping the slope distance between points along the traverse. Underlying strata were examined at pits dug on the lower terrace, on the slope of the riser, and on the upper terrace. A generalized profile of the emergent coastline at the study site is shown in Fig. 3.

Progressing landward, intertidal plants give way to relatively salt-intolerant species until a well-defined beach-fringing forest is reached, consisting primarily of alder and Sitka spruce seedlings and saplings (Fig. 3). A scrub forest of spruce trees densely populates the first few meters directly behind the beach fringe; this forest then gives way to more open terrain with increasingly larger spruce trees with underbrush consisting of devil's club (Oplopanax horridus mig.) and berry bushes (e.g., Rubbes spp.). Decaying alder and berms of littoral debris define older beach lines inside this forest. The forest floor slopes gently upward (5° to 6°) to a prominent riser, 30 to 50 m inland. The elevation at the base of the riser is 6.2 ± 0.1 m above (current) mean sea level (msl). The slope and height of the riser vary from 35° to 45° and 2 to 4 m. The first generation spruce forest

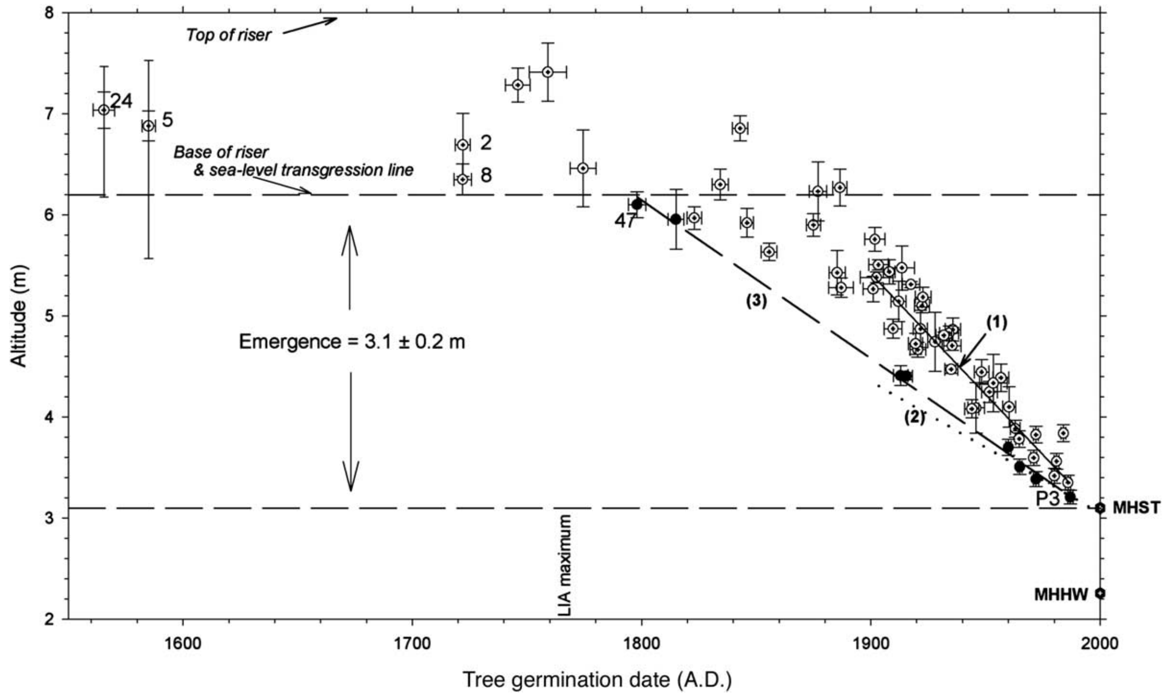

Fig. 4. Germination age vs base elevation of trees at 9-Mile study site. Base of riser indicated by upper dashed horizontal line. Lower horizontal dashed line is the elevation of current mean higher spring tide (MHST), the approximate elevation of where Sitka spruce seedlings are first seen on the modern terrace. Mean higher high water (MHHW) is also indicated. Numbers adjacent to several data points are sample numbers referred to in text. Second set of vertical error bars for trees 5 and 24 indicate the elevation range of their root systems. Numbers in parentheses refer to regressions lines discussed in text. Filled circles are the eldest spruce colonizers at several different elevations.

extends up to and onto this riser. Above the riser lies a terrace with an old-growth forest consisting primarily of western hemlock and Sitka spruce up to 600 years in age. Living spruce of similar age were found on terraces at similar elevations at a number of locations in the Juneau area (Fig. 2). No additional risers were found on the upper terrace.

Organic-rich soil at the beach fringe averaged about 6 cm in depth and increased uniformly with distance to the riser, averaging 20 cm below the riser. On the riser, the organic-rich layer is only 6 to 8 cm thick. Above the riser, on the old-growth terrace, the organic-rich soil exceeds 50 cm in depth and overlies colluvium, old beach deposits, and a diamicton discussed below. In contrast, on the lower terrace, the organic-rich soil layer directly overlies young beach deposits that can be traced downslope to the modern shoreline. These beach deposits lap onto the base of the riser where a thin veneer (6–10 cm) of colluvium, washed from the face of the riser, overlies them. The surficial sediments on both terraces and the riser overlie a diamicton consisting of a till-like mixture of clasts within a generally compact and massive fine-grained matrix. Marine shells retrieved from the top of the diamicton yielded a date of 10,350 ± 70 ^{14}C yr B.P. (Beta-161079). The date and general composition identify it as part of the Gastineau Formation, a locally pervasive 9000 to 12,000 ^{14}C yr B.P. glaciomarine deposit (Miller, 1973).

Tree age vs elevation

Calendar-year germination age vs elevation for a total of 62 trees investigated on the lower terrace and on the riser is shown in Fig. 4. Trees rooted on the slope of the riser germinated as early as the mid 16th century (trees 5 and 24) with several additional trees establishing themselves on the lower slope of the riser during the 18th century (e.g., trees 2 and 8) (Fig. 4). The oldest spruce rooted directly below the base of the riser (tree 47, A.D. 1798) lies at 6.1 msl. The general trend since then has been progressive down-slope migration of spruce trees in response to coastal land emergence. The highest spring tides were observed to briefly inundate the base of the lowest-lying Sitka spruce sapling in the survey (tree P3; Fig. 4).

A linear regression was fitted to data for trees that germinated during the 20th century (line 1, Fig. 4). This line has a slope of 2.4 cm/yr and represents the average rate of downward spruce colonization during the 20th century of all spruce trees sampled in our survey. Line 2 represents the average rate of local land emergence derived from tidal data (Hicks and Shofnos, 1965; Larsen et al., 2003). The slope of this line, 1.3 cm/yr, is based on a linear fit to continuous tidal data since 1936 and a discontinuous series from A.D. 1911 at the NOS Juneau station and at Auke Bay. The rate of uplift recently determined from precision Juneau-area GPS measurements with campaign-style precision is 1.5 ±

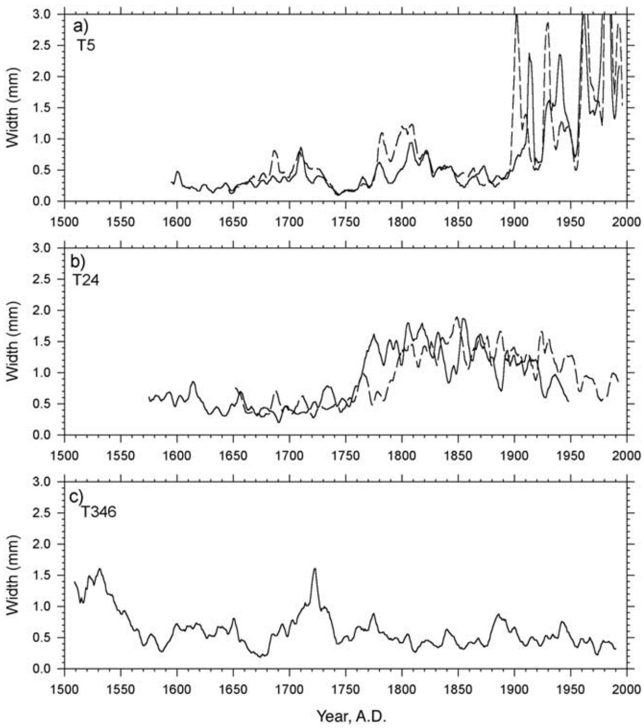

Fig. 5. Ring-width measurements for trees 5 and 24 (a and b, respectively), which are rooted on the riser. A 5-year running average was used to smooth data. The black curves represent cores taken up-slope; dashed lines are cores perpendicular to slope. (c) Data for upper terrace tree 346 are also shown for comparison.

0.1 cm/yr (Larsen et al., 2001). This rate of uplift compares well with the tidal record when the local effect of eustatic rate of sea-level rise (0.1 cm/yr, Larsen et al., 2003) is taken into account. The third line in Fig. 4 is a linear regression fitted to selected outliers of "eldest spruce" at several elevations and includes trees 47 and P3. These trees appear to be the earliest colonizers at their respective elevations in the sample suite. The emergence line was fixed to intercept year A.D. 2000 at an elevation of 3.1 m in Fig. 4, the estimated germination elevation of tree P3, the lowest tree in the survey. The slope of this line is 1.6 cm/yr.

Ring-width measurements

Results of the tree-ring width measurements on cores from trees 5 and 24, which straddle the riser, are presented in Figs. 5a and 5b. These two trees are the oldest spruce in our data set and their position on the slope of the riser would have made them sensitive to sea-level and geomorphic changes induced by sea-level change. The longer time series were derived from cores taken from the up-slope sides of the trees; the shorter records are from cores taken perpendicular to slope direction. A 5-year running average was imposed on the data to smooth high-frequency oscillations and to bring out longer-term trends. Both trees exhibit very narrow rings (average <0.5 mm) for the first century and a half or so of their existence, followed by a pronounced increase in ring-width growth during the latter part of the 18th century (Fig. 5). Ring-width analysis of a 500-year-old spruce tree from the upper terrace is included for comparison (Fig. 5c).

Discussion

Sitka spruce: downward migration vs land emergence

Comparison of the general migration line (line 1) to the land-emergence line (line 2) shows that the average germination lagged behind land emergence documented by tide gauges for much of the 20th century. This average ecesis increases as one goes further back in time, up to 30–40 years during the first part of the 20th century. However, the existence of spruce much older than the average at several different elevations suggests that colonization was possible years before general expansion took place. The trend estimated on the basis of these early colonizers, 1.6 cm/yr, lies much closer to the tidal record, although an ecesis of a few years during the early 20th century is still suggested by comparing the two trends (Fig. 4). Thus, caution must be exercised when attempting to interpret land emergence trends strictly from tree germination records: only the eldest spruce per elevation line should be used to infer such trends. Bégin et al. (1993) found similar results when they examined downward migration of coastal conifers in Hudson Bay and compared them to estimated rates of post-LGM glacier rebound.

The trend of spruce colonization during the 19th century is not as well-defined because our sample density is much lower for this time period. The average colonization rate follows the same trend seen during the 20th century but the early colonizers in our sample set do not follow the trend of line 3. The reasons for this latter difference are unclear. One possibility is that the earliest pioneers from this period somehow eluded sampling. This seems highly unlikely given the size of the study plot and the focus of finding the eldest trees. Another possibility is that the changing rate of colonization actually reflects changes in the rate of emergence. Climate may also have inhibited germination and/or growth. Other possibilities are that the pioneers may have not survived because of saltwater inundation, because of competition, or because of some other cause such as disease or logging.

Sea-level transgression and total land emergence

The results of this study show that the lower terrace is essentially an emerged extension of the present tidal beach and that the riser is clearly a paleo-sea cliff that was eroded landward into the Gastineau Formation. Sea cliff erosion must have essentially ceased by the mid 16th century; otherwise trees 4 and 24 would have toppled over and been destroyed, and other trees would not have been able to germinate on the lower part of the riser. Eustatic rise of sea level could not have been the cause of this sea level transgression as this episode occurred during the Little Ice Age, a period when water was being locked up in glaciers worldwide. Thus, subsidence must have driven this regional transgression.

Studies indicate that moderately cohesive sediments such as those that compose the Gastineau Formation erode with relative ease (Shih et al., 1994), with erosion occurring at mean high spring tide (MHST) with some minimum wind speed to produce waves up to the cliff base (McGreal, 1979). The coast at 9-Mile is well protected and wave heights rarely exceed 0.5 m and are usually much smaller. Assuming that cliff erosion at 9-Mile occurred at MHST or slightly higher elevation, the base of the riser defines the maximum sea-level transgression at MHST: 6.2 $\pm$ 0.1 m above current msl. Tree 47, rooted just below the riser base, provides a nearly identical altitude of 6.1 m. No additional riser was found further inland on the upper old-growth terrace, suggesting that the base of the riser marks the highest sea-level stand after post-Pleistocene rebound.

The lowest tree in the survey, P3, was able to germinate despite brief incursions of saltwater at spring high tides. The estimated germination elevation nearly coincides with the mean MHST for this area: 3.1 m above current msl. Thus, a reasonable estimate for total land emergence is 3.1 $\pm$ 0.2 m. To obtain total uplift one must add the rise in eustatic sea level. Global tide-gauge records indicate little or no rise in sea level in the century prior to A.D. 1880 (Houghton et al., 2001). Using the estimated rate of the local effect of eustatic sea-level rise in the Juneau area during the past century of 0.1 cm/yr, the amount of total uplift in the Juneau area since formation of the riser is estimated to be 3.2 $\pm$ 0.2 m.

This emergence must have begun by A.D. 1798, the germination date for tree 47. However, the question of estimating ecesis remains. Ecesis at Mendenhall Glacier across from 9-Mile ranged from 3 to 8 years for most of the 20th century (Lawrence, 1950; Lacher, 1999) but it could have been much longer at 9-Mile during the late 18th century. Circumstantial evidence for the latter comes from Trees 5 and 24, which exhibit very narrow rings (average $<$0.5 mm) for the first century and a half or so of their existence, followed by a pronounced increase in ring-width growth around A.D. 1770. In comparison, upper terrace tree 346 does not show a comparable change in ring width nor do trees of similar age studied in Mendenhall Valley by Lacher (1999). This comparison suggests that the change in ring widths for trees 5 and 24 was induced by land emergence or some other disturbance such as removal of competing trees rather then climate change. (Tree 5 exhibits a dramatic increase in ring width at around A.D. 1900, which could reflect logging of nearby trees at that time.) Thus, a reasonable estimate for the onset of land emergence is between A.D. 1770 to 1790.

Subsidence and uplift: tectonics or glacier loading?

Several investigators have argued that at least some, if not all, of the current regional uplift in NSEAK is tectonic in origin. Cited as evidence are the scale and pattern of regional uplift (Hudson et al. 1982; Savage and Plafker, 1991), pattern of regional seismicity (Horner, 1983, 1990), and gravity anomalies (Barnes, 1990). However, a close correspondence exists between regional glacial histories and the record of subsidence and uplift shown in this study. This similarity in chronology strongly implicates LIA glacial loading as a contributing if not primary factor driving recent vertical crustal movements. An additional question is whether rapid glacial unloading itself can generate earthquakes (Stewart et al., 2000) and induce episodic rapid uplift. Several factors are examined to help answer regional late-Holocene glacier loading, tectonic processes, or both drive Juneau-area sea-level variations.

1. Regional tectonics

Rapid coseismic subsidence and gradual postseismic uplift (or vice versa) have been documented at several coastal locations around the Pacific Rim, e.g., Prince William Sound and Cook Inlet Alaska (e.g., Atwater et al., 2001), Washington (e.g., Yamaguchi et al., 1997; Benson et al., 2001), and Chile (Atwater et al., 1992). It could be argued that a similar process is responsible for the recent crustal movements in NSEAK. However, all the prior sites occur at subduction-zone-related convergent margins, tectonic settings prone to strong vertical upheavals. In contrast, regional tectonism in NSEAK is dominated by the Fairweather transform fault (FWF) system, a major strike-slip boundary between the North American and Pacific plates (Fig. 1). The closest subduction-related convergent margin setting to Juneau is the Aleutian megathrust, which lies hundreds of kilometers to the northwest.

Measurable vertical movement associated with historic earthquakes on the FWF fault has been very localized and concentrated along the fault (Plafker et al., 1994). In addition, recent measurements of relative plate motion along the FWF have found motion to the south of Yakutat to be almost entirely strike-slip with little or no convergence across the fault (Fletcher and Freymueller, 1999; Larsen et al., 2001). Neither has there been any documented Holocene movement on the Denali–Chatam Strait transform fault system (DCSF) (Plafker et al., 1994), which lies 30 km west of Juneau (Fig. 1), nor has any relative motion been observed by GPS measurements along this system (Larsen et al., 2001). The Juneau area itself is relatively aseismic (Alaska Earthquake Information Center) and no large earthquakes are reported in Juneau historic records (ca. A.D. 1880). There is also no mention of large earthquakes in local Tlingit native oral traditions, although the LIA advance does figure prominently in them (Nyman and Leer, 1993; Cruikshank, 2001). Thus, the lack of trans-plate convergence, distance from active faults, and current and past aseismicity in Juneau argue against tectonic activity being a major cause of late-Holocene sea-level variations in the Juneau area.

2. Comparison to glacier load history

The LIA was underway by the 13th century and glacier expansions filled both arms of Glacier Bay and caused Taku Glacier to advance and close off Taku River (Goodwin, 1988; Motyka and Beget, 1996) (Fig. 1). Although the LIA continued well into the 19th century, there was a region-wide glacier retreat from LIA maximums that began during the mid to late 18th century (Lawrence, 1950; Goodwin, 1988; Post and Motyka, 1995; Motyka and Beget, 1996). Non-tidewater glaciers retreated very slowly through the late 18th and 19th centuries and a few even experienced standstills and slight advances (Lawrence, 1950; Lacher, 1999; Motyka and Beget, 1996; Motyka et al., 2002). In contrast, tidewater glaciers in Glacier Bay and Taku Glacier from the Juneau Ice Field underwent rapid and substantial tidewater calving retreats during the same period (Goodwin, 1988; Post and Motyka, 1995). Once tidewater calving glaciers retreat into deep water, they become unstable and undergo a rapid retreat that is independent of climate, as part of the “tidewater glacier cycle” (Post and Motyka, 1995). The main trunk glaciers at Glacier Bay retreated a total of 120 km from Icy Straits to the head of the west arm of the bay in just 180 years, ranking it as the fastest and most prolonged historic tidewater calving retreat in Alaska. This calving retreat caused immense and rapid glacial unloading, with the effects on the Earth’s crust likely to be regional in extent (Larsen et al., 2003). Although Glacier Bay is considerably further away (120 km) from Juneau than the Juneau Ice Field (30 km), ice fields there covered at least twice as much area as the Juneau Ice Field during the LIA, and post-LIA ice loss volume was at least an order of magnitude greater and more rapid at Glacier Bay. Regional tidewater glacier retreat finally slowed and some glaciers even began readvancing during the 20th century (Molenaar, 1990; Motyka and Beget, 1996). In contrast, the rate of wastage of non-tidewater glaciers increased significantly during the 20th century (Arendt et al., 2002; Motyka et al., 2002).

This history of regional LIA glacier loading and unloading coincides well with the timing of sea-level transgression, sea-cliff erosion, and the subsequent onset of uplift and its continuation documented in this study. Trees on and below the riser indicate sea level stabilized by about A.D. 1560, approximately 200 years before glaciers began retreating, and then began falling during the late 18th century. The hiatus in sea-level rise may indicate that regional glacier loads stabilized by the end of the 16th century and did not appreciably expand over the next two centuries. If so, this would imply a relatively low mantle viscosity in order for the crust to adjust to glacial loads so rapidly (see discussion below). The record of land emergence since about A.D. 1770–1790 has closely followed the unloading that Glacier Bay experiencing during the late 18th century and the 19th century and the rapid wastage of other regional glaciers during the 20th century.

3. Gradual vs episodic post-LIA uplift

Several considerations indicate that Juneau area uplift has been gradual rather then caused by a single or a series of sudden large coseismic movements. The first is that the tide-gauge record at Juneau shows a steady rate of relative sea-level fall since A.D. 1911. In contrast, coseismic uplift is readily apparent as jumps in tide-gage records for stations more proximal to tectonic forcing (Larsen et al., 2003). The second factor is that coseismic uplift would have left a band of coastal tidelands available for immediate colonization. Thus one would expect to find a step covered with a forest of trees having approximately the same age. Instead, tree age increases steadily from the beach to the riser, which suggests a continuous process of emergence. In addition, there is no evidence of a riser below the LIA riser that should have been constructed if uplift were episodic rather then gradual. Aggradation of organic-rich soil also appears to follow a uniform pattern from beach to riser with no indication of stepwise accumulation of debris.

4. Glacier rebound models

Global glacial isostatic adjustment (GIA) models are poorly resolved for the study area due to limited knowledge of the LGM ice-sheet history here (e.g., Tushingham and Peltier, 1991). However, to the south in the northern Cascadia subduction zone, Clague and James (2002) constructed a regional post-LGM rebound model with a detailed Cordilleran ice sheet history. This model predicts present-day uplift rates less than 0.1 mm/yr, lower than ICE-3G predictions by an order of magnitude (Tushingham and Peltier, 1991). Moreover, ICE-3G uplift predictions for the Juneau study area are <1 mm yr^{-1}, a small fraction of the regional uplift rates.

Larsen et al. (2003) modeled LIA glacier isostatic rebound in southern Alaska using an Earth model described in detail by Ivins and James (1999) and a combination of regional and Glacier Bay LIA glacial histories. The resulting uplift rates closely matched tide-gauge observations (Hicks and Shofnos, 1965; Larsen et al., 2003) when a low viscosity ($\sim 3.5 \times 10^{19}$Pa s) Earth model is used. Thus, based on the study of Larsen et al. (2003), the rapid uplift observed in southeast Alaska could be accounted for by post-LIA glacial isostacy without need of invoking tectonic forcing.

It is interesting to note that Horner (1983, 1990) ascribed uplift in Glacier Bay to tectonics because of the level of seismicity detected in its the northern region. This zone of seismicity lies in a location that was the likely center of the LIA ice cap (Fig. 1) and therefore probably experienced the greatest magnitude of post-LIA glacier unloading. Given the apparent lack of convergence across the FFW, it is intriguing to speculate that glacier rebound from the rapid post-LIA unloading rather then tectonics is causing this seismic activity

Conclusions

Dendrochronology in combination with geomorphology and other observations has enabled accurate determination of a sea-level transgression, which is informally called the "Little Ice Age Transgression." For Juneau this transgression lies at 6.2 m above current mean sea level, at the base of a well-defined paleo-sea cliff eroded in a late-Pleistocene diamicton. Dendrochronology also established the onset of land emergence at between A.D. 1770 and 1790; these dates coincide with regional glacier retreat from mid 18th century LIA maximums. Total emergence since onset has been 3.1 ± 0.2 m. Total uplift has been 3.2 m when the local effect of eustatic sea-level rise is taken into account. The average rate of downward migration of Sitka spruce lagged behind the rate of land emergence as defined by local tide gauge records during the early part of the 20th century. However, outliers of early colonizers closely approximate the trend defined by the tidal records.

Several lines of evidence indicate that LIA glacier expansion and post-LIA retreat have been the primary mechanisms responsible for subsidence and uplift in the Juneau area during the last several hundred years. These include (1) the close correspondence between coastal dendrochronology and regional glacier records; (2) the tectonic setting, lack of convergence across plate boundaries, and the distance of the site from active faults; (3) the gradual nature of uplift reflected in both age vs elevation of tree germination and the tide-gauge record; and (4) the results of preliminary modeling of post-LIA glacial rebound. Climate change rather then regional tectonics appears to have forced relative sea-level change in the Juneau area over the last several hundred years. The presence of a tectonic component in Juneau area uplift cannot be ruled out. However, such a component, if it exists, is likely to be quite small. Regional application of the methodology described here, in conjunction with sea-level changes derived from tidal records, would provide a robust set of data that can be used to constrain future models of regional glacier rebound.

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