Late Miocene exhumation and uplift of the Washington Cascade Range

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ABSTRACT

The Washington Cascade Range is a complex, polygenetic mountain range that dominates the topographic, climatic, and cultural configurations of Washington State. Although it has been the locus of ongoing arc magmatism since the Eocene, most of the range is distinct from the southern part of the arc in Oregon and California in that bedrock uplift has produced high surface elevations and topographic relief, rather than volcanic burial or edifice construction. (U-Th)/He and fission-track ages of bedrock samples on the east flank of the range record relatively rapid cooling in the early Tertiary, but slow exhumation rates (~0.2 km/m.y.) through most of the Oligocene. Samples on the west flank suggest rapid cooling in the late Miocene (8–12 Ma), and age variations in vertical transects are consistent with a pulse of rapid exhumation (0.5–1.0 km/m.y.) at that time. Apatite He ages as young as 1–5 Ma in several areas suggest that high cooling and possibly exhumation rates persist locally. Accelerated exhumation rates ca. 10 Ma are also observed in the Coast Mountains of British Columbia and southeast Alaska, ~1500 km to the north, suggesting a large-scale mechanism for the exhumation pulse at that time.

Keywords: (U-Th)/He, thermochronology, apatite, Cascades, Washington.

INTRODUCTION

The Cascade Range in Washington State (Fig. 1) forms an important regional geologic, climatic, and cultural boundary. Numerous studies focusing on the high-temperature geologic history (especially of the northern part of the range) have documented a series of terrane-accretion episodes in the Cretaceous and Eocene, accompanied by crustal thickening, plutonism, and large-scale strike-slip faulting (e.g., Haugerud et al., 1994; Cowan et al., 1997; Whitney et al., 1999). As is the case farther south in Oregon and California, east-directed subduction has been ongoing off the coast of Washington since ca. 40 Ma, resulting in locally thick accumulations (3–5 km) of volcanic rocks with ages dominantly between 15 and 36 Ma. Aside from five Quaternary stratovolcanoes however, little of the modern topographic expression of the Washington Cascade Range is due to volcanism. Instead, the bedrock geology north of Snoqualmie Pass is dominated by crystalline rocks uplifted relative to the surrounding Puget lowlands and Columbia basin. Indirect evidence, such as warping of ca. 15–16 Ma Columbia River Basalt Group lavas, suggests that at least some of this uplift is younger than middle Miocene.

We determined apatite and zircon (U-Th)/He and apatite fission-track ages (see GSA Data Repository supplementary information for sample locations, data, and analytical details[1]) from plutonic and metamorphic rocks in three regions in the Washington (and southern British Columbia) Cascade Range, here termed the west flank, east flank, and north Cascades regions (Fig. 1). Samples along vertical transects of ~1.1 and 1.7 km of relief over distances of <~5 km were collected in the east and west flank groups; a shorter ~0.8 km transect was collected across an ~25 km distance in the north Cascades region.

Use of low-temperature thermochronometers (closure temperatures ~70–180 °C) requires consideration of potential spatial and temporal variations in geothermal gradients. Modern gradients in most locations in the Washington Cascade Range north of Mount Rainier are 20–40 °C/km with regionally higher gradients largely restricted to a narrow zone between Mount St. Helens and Mount Adams (Blackwell et al., 1990). However, geothermal gradients at the time of cooling through apatite He and apatite fission-track closure temperatures may have been higher in some areas, especially in the west flank region in and near the 17–25 Ma Snoqualmie batholith (Erikson, 1969; Tabor et al., 2000). Dacitic intrusions with 4–8 Ma ages are also present northeast of Mount Rainier (Armstrong et al., 1976; Smith et al., 1989; P.E. Hammond, 2002, personal commun.), although our samples were collected tens of kilometers away from these intrusions. In the north Cascades region, apatite fission-track ages of samples may have been affected by the 16–18 Ma Mount Barr pluton (Holunga, 1996) or Chilliwack batholith or younger intrusions near Mount Baker. In most of our samples, however, apatite He ages are significantly younger (by at least 5–10 m.y.) than higher temperature ages of intrusions, suggesting that in most cases apatite He ages reflect cooling primarily by surface erosion.

RESULTS AND DISCUSSION

West Flank and North Cascades Regions

Apatite and zircon (U-Th)/He and fission-track ages are plotted against elevation in Figure 2 (see footnote 1). In the west flank and north Cascades sample groups, apatite He ages do not vary systematically with elevation, and nearly all are between 6 and 12 Ma. Exceptions are a sample from near the town of Index at 13.5 Ma, two samples from northeast of Mount Rainier at 5 Ma, and samples from the 2.5 ± 0.1 Ma Lake Ann pluton (James, 1979) at 1.3–2.0 Ma. Assuming geothermal gradients between 20 and 40 °C, the abundant 6–12 Ma apatite He ages in the north Cascades and west flank regions require that at least 1.5–3 km of crust have been eroded from the surface since that time. The steep age-elevation correlations and scatter in both sample groups do not allow precise constraints on apparent exhumation rates in these regions, but if the Granite Mountain ages in the west flank group are due primarily to cooling by exhumation (rather than magmatic cooling of the Snoqualmie batholith), they indicate an apparent exhumation rate of 0.5–1.0 km/m.y. (Fig. 2). The much older apatite fission-track age at a high elevation (43 Ma) in the west flank, however, limits total post-Eocene erosion to <~3–5 km. Differences between apatite fission-track and apatite He ages in the north Cascades group suggest that prior to the

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[1] GSA Data Repository item 2002088, Apatite and zircon (U-Th)/He and apatite fission-track sample locations, data, and analytical methods, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

Geology; September 2002; v. 30; no. 9; p. 767–770; 3 figures; Data Repository item 2002088.

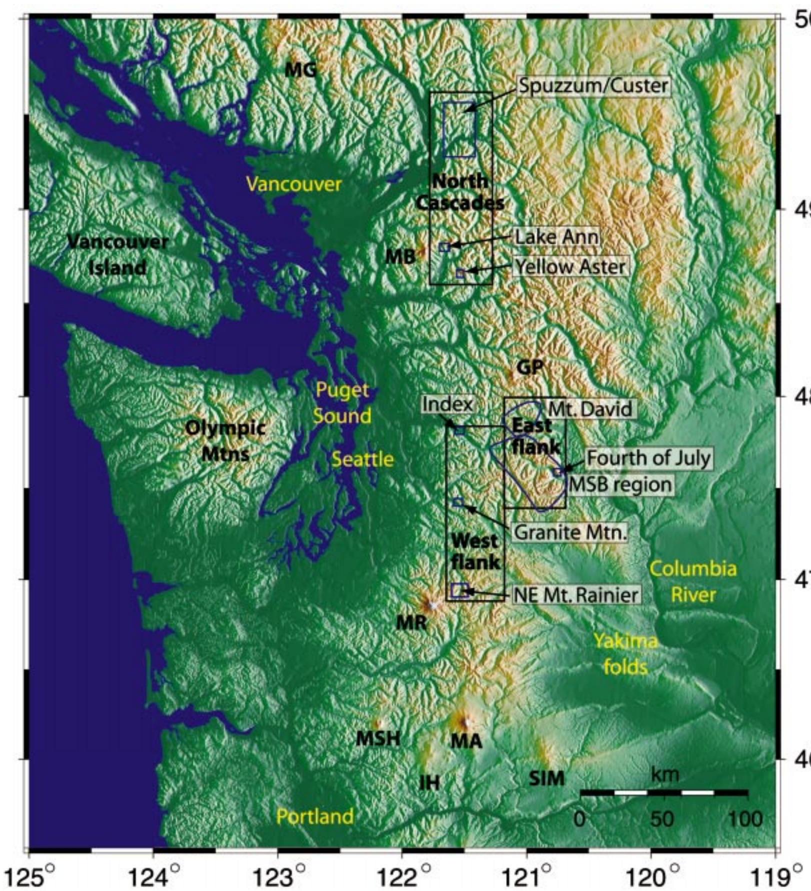

Figure 1. Map of Washington Cascade Range and surrounding region. Boxes enclose three primary sample regions, and blue lines enclose specific regions, referred to in text, Figure 2, and GSA Data Repository item (see text footnote 1). MSB—Mount Stuart batholith. Quaternary volcanoes of or near modern arc: MG—Mount Garibaldi, MB—Mount Baker, GP—Glacier Peak, MR—Mount Rainier, MSH—Mount St. Helens, IH—Indian Heaven volcanic field, MA—Mount Adams, SIM—Simcoe.

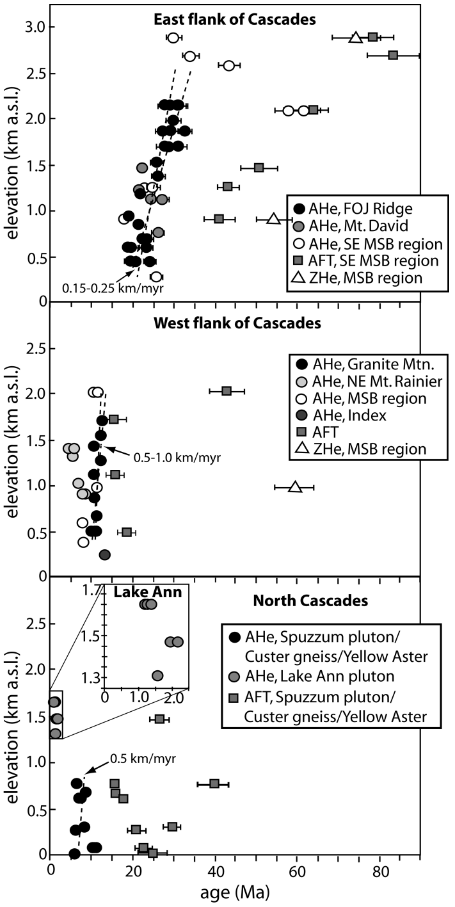

Figure 2. (U-Th)/He and apatite fission-track (AFT) ages of Washington (and southern British Columbia) Cascade Range samples, plotted against elevation. Error bars are 2σ for (U-Th)/He and 1σ for AFT. See text footnote 1 for detailed data tabulation. MSB—Mount Stuart batholith, FOJ—Fourth of July; a.s.l.—above sea level.

late Miocene, cooling and most likely exhumation rates were relatively slow, ∼0.05–0.2 km/m.y., depending on geothermal gradients. If the Granite Mountain transect reflects 0.5–1.0 km/m.y. exhumation at 10–12 Ma, exhumation rates must have since decreased by at least a factor of 2–4, because such rates would produce ages of 2–4 Ma if ongoing today.

East Flank Region

In the east flank region, apatite He ages range from 18 to 60 Ma and show a broad correlation with elevation, especially within the 1.7 km Fourth of July vertical transect (Fig. 2). This transect yields an apparent exhumation rate of 0.15–0.25 km/m.y. through most of the Oligocene to early Miocene. A group of samples from various locations in the southeast corner of the Mount Stuart batholith region falls in the vertical transect trend below an elevation of ∼2 km, but those above 2 km show no correlation with elevation. One of these high-elevation samples has the oldest apatite He age (60 Ma)—only slightly younger than its 64 Ma apatite fission-track age. These old cooling ages require that at least locally on the east flank, exhumation was limited to <∼2–3 km since the early Tertiary. Most apatite fission-track ages of east flank samples are relatively old, between 41 and 83 Ma. With the exception of one sample, these ages are an average of 33 m.y., and a minimum of 20 m.y., older than apatite He ages on the same samples or on samples at similar elevations. These age differences require slow time-averaged cooling (1–2 °C/m.y.) between apatite fission-track and apatite He closure in the early to mid-Tertiary (exhumation rates of only ∼0.02–0.10 km/m.y.)—consistent with the ∼0.05 km/m.y. slope of the east flank apatite fission-track data.

Although there is no direct thermochronometric evidence in the east flank samples for rapid late Tertiary exhumation, the combination of old cooling ages (60–80 Ma) and the modern high local relief (2–3 km) on the east side is consistent with a recent increase in uplift and exhumation rates that has removed <2–3 km of rock. Correlations between relief and erosion rates worldwide suggest that regions with 2 km of local relief are generally subject to mean erosion rates of at least ∼0.4 km/m.y. (e.g., Pazzaglia and Brandon, 1996). If this is the case on the east flank of the Cascades, these high exhumation rates could not have begun earlier than ca. 8 Ma, because old cooling ages at high elevations in this region limit total erosion to <∼3 km. Thus the inferred late Miocene uplift that affected the west flank may have also increased relief and surface uplift on the east flank.

Late Miocene Uplift

Taken together, the distribution of (U-Th)/He and apatite fission-track ages in this study supports a general model for the modern Washington Cascade Range involving slow exhumation from the Eocene to late Miocene at ≤0.25 km/m.y. Most west flank and north Cascades samples show rapid late Miocene cooling that produced widespread 6–12 Ma He cooling ages and steep age-elevation correlations. It is difficult to rule out the influence of postmagmatic thermal relaxation on these rapid cooling rates in some areas, but if the west flank age-elevation data are interpreted as reflecting exhumation, they imply a pulse of 2–3 km of erosion in the late Miocene, at rates of 0.5–1.0 km/m.y.

A variety of other geologic evidence supports an episode of uplift and erosion in the Washington Cascade Range in the late Miocene. Eocene nonmarine sedimentary rocks on both sides of the range record drainage of mountainous regions hundreds of kilometers to the east, across the location of the modern Cascade Range (Tabor et al., 1984; Gresens, 1987; Vance et al., 1987). In addition, 3–5-km-thick sequences of late Eocene through early Miocene volcanic rocks are present in and adjacent to the Cascade Range, requiring lack of significant erosion, and local subsidence and burial of the range, through this time. Middle Miocene (ca. 15 Ma) basaltic lavas of the east-derived Columbia River Basalt Group are tilted and uplifted along the eastern edge of the range; near Mount Rainier these lavas reach elevations more than 1.5 km higher than correlative units to the east (Swanson, 1997). Warping and uplift of Ellensburg and Simcoe units on the east side of the range also suggest an initiation of uplift between 10 and 4.5 Ma (Hammond, 1979). Plant and pollen fossils from interbeds in the Columbia River Basalt Group throughout central and eastern Washington and northwestern Idaho consistently indicate a warm, relatively mesic climate, comparable to that in the southeastern United States today, through the late Miocene (Chaney, 1938; Berry, 1929; Smiley and Rember, 1979; Barnett and Fisk, 1980; Wolfe, 1981); such a climate may imply the absence of the Cascades orographic barrier to Pacific-derived precipitation.

Although there are some ca. 5–15 Ma arc magmatic rocks in the Washington Cascade Range (e.g., Hagstrum et al., 1998; Smith, 1988; Smith et al., 1989), they are relatively rare; in general, there is a distinct paucity of volcanic rocks of this (or some similar) age range (Mattinson, 1977; Evarts et al., 1987; Swanson et al., 1989; Smith, 1993; Evarts and Swanson, 1994). This gap is in spite of the fact that plate tectonic reconstructions indicate a convergent boundary and subduction off the west coast of Washington since at least the Eocene (Brandon and Vance, 1992). As suggested by others (e.g., Smith, 1993), the paucity of magmatic rocks of this age may be simply due to lack of preservation because of accelerated uplift and erosion in the late Miocene, rather than to an actual decline in arc magmatic production.

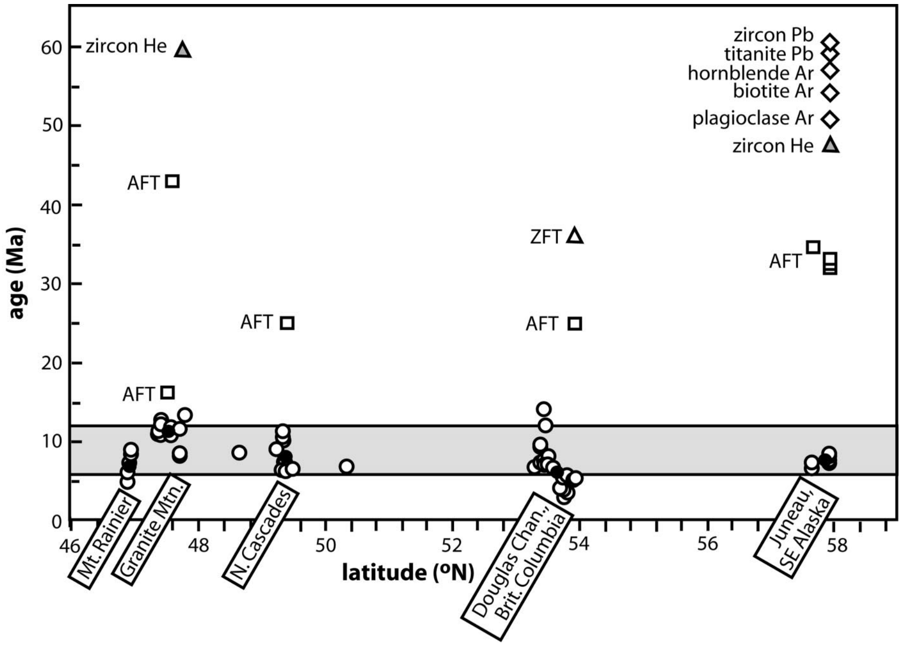

Figure 3. Apatite He ages (white circles) plotted against latitude for west flank and north Cascades samples from Washington State, and sea-level samples from British Columbia (Farley et al., 2001) and southeast Alaska (Hickes et al., 2000; Hickes, 2001). Gray box is 12–6 Ma age range that encompasses regionally averaged apatite He ages (black circles). Other symbols represent cooling ages from other radioisotopic systems (Parrish, 1983; Donelick, 1986; Gehrels et al., 1991; Wood et al., 1991). AFT—apatite fission-track; ZFT—zircon fission-track.

Uplift of the Northwest Cordilleran Margin

Thermochronometric and geologic studies of the Coast Mountains in British Columbia and southeast Alaska, as far as 1500 km to the north (Fig. 3), indicate a Cenozoic uplift history similar to that of the Washington Cascades, despite the subduction to transform plate-boundary change in southern British Columbia. Exhumation histories for the Coast Mountains involve slow cooling and little to no exhumation from the Eocene through late Miocene, followed by accelerated exhumation beginning ca. 10 Ma (0.2–0.5 km/m.y.) (Parrish, 1983; Donelick, 1986; Hickes et al., 2000; Farley et al., 2001; Hickes, 2001). Similar to other geologic constraints in Washington, the timing and rates of rock and surface uplift in the Coast Mountains are also defined by uplifted late Miocene basalts (Parrish, 1983) and paleobotanical climatic indicators (Rouse and Mathews, 1979) east of the range. If the uplift and exhumation of the Washington Cascade Range is genetically related to that of the entire northwest Cordilleran Coast Mountains, the mechanism is of larger scale than simply localized rotation in the U.S. Pacific Northwest or arc magmatic crustal thickening.

One possible mechanism for continental-margin–scale rock and surface uplift starting at 12–6 Ma is simply a change in relative North American–Pacific plate motion. Plate reconstructions show that such a change in relative plate motions ca. 8 Ma had a wide-ranging effect on Neogene tectonics in the southwestern United States (Atwater and Stock, 1998). Another possible mechanism is delamination of lower crust by convective instability beneath the entire length of the northwestern coastal Cordillera at 12–6 Ma. Crustal thicknesses in the Washington Cascade Range and British Columbia Coast Mountains are only ~30–40 km, and no sign of a significant mafic root is observed (Parsons et al., 1998; Morozov et al., 1998), as would be required for generation of intermediate-composition volcanic rocks in the Cascade Range and the massive Coast Plutonic Complex in British Columbia from arc magmatism. Finally, evidence for accelerated exhumation rates in the late Miocene is common not just in the northwest Cordillera, but in many other locations on the Pacific rim and elsewhere. While recent attention has generally focused on Pliocene to Holocene climate change, most compilations show an earlier onset, with significant acceleration in the late Miocene (e.g., Lear et al., 2000). It is not inconceivable, although it is difficult to test at this point, that some component of climate change alone (such as the onset of 10^3–10^5 yr climatic oscillations) accelerated erosional exhumation rates. In the Cascades, however, this would mean that an inference of late Miocene surface uplift from paleobotanical evidence east of the Cascades is incorrect—possibly an artifact of climate change.

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