Holocene strath terraces, climate change, and active tectonics: The Clearwater River basin, Olympic Peninsula, Washington State

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ABSTRACT

The ~400 km² Clearwater River basin, located on the Pacific flank of the actively uplifting Olympic Mountains of western Washington State, contains a well-preserved flight of Holocene fluvial terraces. We have collected a large data set of numeric ages from these terraces that is used to elucidate the geomorphic, fluvial, active tectonic, and climatic processes that operate at Holocene spatial and temporal scales. Detailed field mapping reveals three prominent Holocene straths and their overlying terrace deposits. Terrace ages fall into three broad ranges: ca. 9000–11 000 yr B.P. (Qt4), 4000–8000 yr B.P. (Qt5), and 0–3000 yr B.P. (Qt6). Terrace deposit stratigraphy, sedimentology, and age distributions allow us to consider two alternative models for their genesis. The favored model states that the terrace ages are coincident with lateral incision of the Clearwater channel, emplacement of the terrace alluvium, and the carving of the straths. Vertical incision of the Clearwater channel was primarily relegated to the brief (~1000 yr) intervals when we have no record of terraces. Alternatively, the straths were carved as the channel incised vertically during the brief time periods between dated terrace deposits, and the terrace ages record a subsequent long time of alluviation atop the straths and concomitant termination of vertical incision. In both models, we envision a Clearwater River channel at or near capacity with a temporally variable rate of both lateral and vertical incision. Small deviations from this at-capacity condition are driven by variations in the liberation and delivery of hillslope sediment to the channel. We consider several causes for variable hillslope sediment flux in this tectonically active setting including Holocene climate change and ground accelerations related to earthquakes. Holocene rates of vertical incision are reconstructed along nearly the entire Clearwater Valley from the wide distribution of dated terraces. Incision rates clearly increase upstream, mimicking a pattern documented for Pleistocene terraces in the same basin; however, the rates are 2–3 times those determined for the Pleistocene terraces. The faster Holocene incision rates may be interpreted in terms of an increase in the rates of rock uplift. However, we favor an alternative explanation in which the Holocene rates represent a channel rapidly reacquiring its stable, graded concavity following protracted periods of time in the Pleistocene when it could not accomplish any vertical incision into tectonically uplifted bedrock because the channel was raised above the bedrock valley bottom by climatically induced alluviation. These results illustrate how, even in tectonically active settings, representative rates of rock uplift inferred from studies of river incision should be integrated over at least one glacial-interglacial cycle.

Keywords: geomorphology, Holocene, paleoclimate, radiocarbon dating, terraces.

INTRODUCTION

River terraces are preserved in a wide range of active tectonic settings and watershed sizes. Mapped, correlated, and dated terraces form the basis of our understanding of how river systems evolve. In the active tectonic setting, the history of fluvial processes is both a direct consequence of and has a dynamic interaction with rock deformation (Bull and Kneepf, 1987; Wells et al., 1988; Merritts et al., 1994; Personius 1995; Gardner et al., 1992; Burbank et al., 1996; Maddy, 1997; Pazzaglia et al., 1998; Hancock et al., 1999). A key debate that has overshadowed more than three decades of intense characterization of fluvial systems in tectonically active settings is how tectonic processes can be isolated from the myriad of geomorphic processes that also influence the genesis and subsequent preservation of fluvial stratigraphy (Schumm, 1969; Schumm et al., 1987; Bull, 1990, 1991; Sugai, 1993; Tucker and Slingerland, 1997; Hancock and Anderson, 2001). For example, rapid rates of rock uplift and changes in base level that accompany both co- and interseismic deformation introduce the potential for rivers to incise and abandon their valley bottoms as they seek a new base level of erosion (Gilbert, 1877; Bull, 1991). But the precise manner in which the rivers accomplish that incision and what terrace record will be left behind appears to be dominated by how the watershed responds to changes in climate—most notably, glacial-interglacial–scale climate change (Bull, 1991). Because climate change tends to occur more frequently than secular changes in the rates of rock uplift, actively incising rivers have the potential to leave a relatively high-resolution record of their incision. The rate of fluvial incision is commonly interpreted in terms of the rate of rock uplift with the built-in assumption that terrace formation is a short-term disequilibrium phenomenon oscillating about a long-term equilibrium profile (Mackin, 1948) more or less represented by the physical characteristics of the modern profile (Knox, 1975; Bur-
With these debates and assumptions in mind, we set out to map, describe, and date a suite of Holocene fluvial terraces preserved astride an actively uplifting forearc of the Cascadia subduction margin. These terraces preserve a high-resolution record of river incision over relatively short (10³ yr) time scales that can be interpreted in terms of subduction-zone and upper-plate earthquakes (Atwater, 1987, 1992; Atwater and Hemphill-Haley, 1997), contemporary surface deformation (Savage et al., 1991; Dragert et al., 1994), changes in Holocene climate (Bond et al., 1997; Gavin et al., 2001), and the liberation of hillslope regolith (Reneau et al., 1989; Reneau and Dietrich, 1991). The motivation for the study comes from ample opportunity for 14C numeric age control, in the form of organic material preserved in the terrace deposits, and the opportunity to compare Holocene-scale to Pleistocene-scale rates of fluvial incision (Pazzaglia and Brandon, 2001) as well as Neogene-scale rates of exhumation (Brandon et al., 1998). We seek to demonstrate the conditions under which Holocene terraces form and establish limits to some of our assumptions as to how these terraces can be used to interpret the nature and rates of active tectonic processes.

SETTING

The Olympic Mountains of western Washington are the northernmost extension of the Cascadia margin Coast Ranges (Fig. 1A). The Olympics represent a prominent forearc high produced by northeast-directed oblique subduction of the Juan de Fuca plate beneath North America at a present plate-convergence rate of ~36 mm/yr (DeMets and Dixon, 1999). With an area of ~7700 km², the Olympic Mountains are the highest part of the Coast Ranges with the high point, Mount Olympus, reaching 2427 m. The range has a general domal shape and a distinct radial drainage pattern with stream headwaters and highest elevations centered on Mount Olympus. Most of the moisture falls on the Pacific-facing, western slopes. Major streams here have decidedly concave-up profiles and knickpoints confined primarily to upstream reaches where channel slopes are very steep. The valleys have developed along Neogene northeast-trending structures interpreted as strike-slip faults, such as the Clearwater River shear zone (Stewart, 1970; Gerstel and Lingley, 2000). The streams have mixed bedrock and alluvial channels, mostly in glacially modified valleys. It is common to find ~3 m of alluvium in the channels atop the bedrock thalweg.

The Olympic Mountains are cored by the Olympic subduction complex, an Oligocene–Quaternary accretionary wedge up to 30 km thick composed of stratigraphically discontinuous Neogene–Quaternary clastic, marine sedimentary and shallow-intrusive and extrusive, intermediate to mafic igneous rocks. These rocks, exposed in the core of the range, were
from the basin headwaters in early or pre-Wisconsinan time. There are radiocarbon-dead (>45 ka) lacustrine deposits overlying a lodgment till at this location (Wegmann, 1999). The lack of an extensive tongue of ice scouring the entire Clearwater Valley has permitted the basin to preserve a fine suite of river terraces that have been mapped, described, and used to infer Pleistocene rates of fluvial incision (Wegmann, 1999; Pazzaglia and Brandon, 2001).

Hillslope processes throughout the Olympic Mountains are dominated by bedrock-involved landslides, debris flows, and colluvial creep down the ubiquitous steep hillslopes (Reid and Dunne, 1984; Serdar, 1999; Gerstel, 1999). Debris flows in low-order drainages are very active, but may have been even more prevalent near the Pleistocene-Holocene boundary as suggested by the excavation of colluvial hollows (Reneau et al., 1989). Climatically driven introduction of sediment to the fluvial system from hillslope colluvial hollows has been used to explain the creation of a widespread and well-preserved strath terrace in the Coast Range of Oregon at ca. 8–12 ka (Personius et al., 1993).

The lower reaches of the Clearwater basin have been logged for the past seven decades, but in the past 40 yr, rapid clear-cutting throughout the upper two-thirds of the basin has removed ~75% of the original forest cover (J. Cederholm, 2001, personal commun.). One consequence of stream-adjacent logging has been the removal of the natural source of large woody debris (LWD). Abundant LWD in stream channels has been demonstrated to be an effective ephemeral trap for transported alluvium in unlogged, glaciated watersheds (Abbe and Montgomery, 1996a); however, the relatively steeper fluvial gradients of the glacier-free Clearwater Valley have limited the retention of LWD in the main channel with respect to the Queets and Hoh Valleys (J. Cederholm, 2001, personal commun.). Logging activity may also be associated with the widespread accumulation of silt on the flood plains and sand and gravel on elongate midchannel bars. The flood plains and bar islands nearly everywhere have a community of similar-aged red alders (*Alnus rubra*) that core samples reveal to be ~30 yr old (Wegmann, 1999). The nearly uniform age of the floodplain alder stands is generally coincident with the onset of intense clear-cutting.

**FLUVIAL TERRACES**

River terraces are the geomorphic and sedimentologic expression of form and process adjustments in a fluvial system (Schumm et al., 1987). Terraces are unconsolidated, allostratigraphic units with a basal unconformity called a "strath" typically cut across bedrock and a constructional bench-like top called a "tread" (Fig. 2). The terrace deposit between the strath and tread varies in texture, stratification, and thickness. When it is thin (<3 m), it represents essentially all of the sediment in transport in a bedrock or mixed bedrock and alluvial channel during bankfull or larger discharges (Wolman and Miller, 1960). In contrast, thicker terrace deposits represent alluvial valley fills that lift the channel off the strath for some period of time (Bull, 1991). For the sake of simplicity, the following discussion will be limited to consideration of incision of mixed bedrock and alluvial channels in which straths typically have low relief and the terrace deposits are relatively thin (Fig. 2B). Such terraces are commonly called "strath terraces" (Bull, 1991).

The process of carving a strath, although not well understood, can be readily observed for many bedrock and mixed bedrock and al-
luvial channels (Gilbert, 1877; Mackin, 1937). In these settings, the width of the valley bottom roughly corresponds to the limits of lateral channel corrosion (Fig. 2A). Alluvium underlaying the flood plain typically is not thicker than ~3 m, and during low-flow conditions bedrock exposed in the channel bottom can be observed to project laterally as the base of the flood plain. Tributary streams incised through the flood plain provide additional windows of observation confirming that the bedrock exposed in the active channel continues laterally as the unconformity at the base of the valley bottom (Fig. 2A). In this respect, the strath of a terrace is the paleo-valley-bottom base, and the terrace tread is the constructional top of the (commonly modified) paleo-flood plain (Fig. 2A).

Straths represent a time when the channel and the alluvium undergoing transport are in direct communication with the underlying bedrock. Thus, first-order channel characteristics such as gradient and concavity are probably most similar between the modern channel and paleochannels during periods of strath cutting. These are the conditions under which the assumption of using a modern river’s longitudinal profile as a long-term proxy for the equilibrium profile has the greatest chance of being valid (Burbank et al., 1996; Pazzaglia and Brandon, 2001). The assumptions of similar channel gradient and concavity cannot be so readily assumed when considering the terrace treads and the flood plain, especially when the terrace deposits are thick and the flood plain represents the constructional top of a thick valley-bottom fill.

Strath terraces are common and typically unpaired in tectonically active areas (Bull, 1991), but they may extend for many kilometers along the length of a valley. It has become clear from diverse tectonically active settings that even though terraces may lie at variable distances above the modern valley bottom, their ages tend to cluster around dates temporally coincident with known climatic changes (Bull and Knuepfer, 1987; Merritts et al., 1994; Burbank et al., 1996; Pazzaglia et al., 1998; Fuller et al., 1998; Hancock et al., 1999). Geomorphologists have long appealed to the impacts of climate change on the fluvial system as the driving mechanism behind those modifications of channel form and process that alternately widen and narrow the valley bottom and ultimately lead to the genesis and preservation of strath terraces (Schumm, 1969; Bull and Knuepfer, 1987; Bull, 1991; Pazzaglia and Gardner, 1993; Meyer et al., 1995; Pazzaglia and Brandon, 2001).

METHODS

We have carefully mapped strath terraces at a 1:12,000 scale in the Clearwater basin (Wegmann, 1999). The mapping was carried out on foot and by repeated canoe traverses. Minimum strath ages are provided by radiocarbon dates from organic material preserved in the overlying terrace alluvium (Figs. 1C and 2B). We started with the reasonable assumptions that the alluvium overlying the strath is genetically related to the strath cutting (Gilbert, 1877; Mackin, 1937; Hancock and Anderson, 2001), that the straths were not subsequently reoccupied by the active channel (Merritts et al., 1994), and that the organic material is rarely recycled from older deposits nor is it representative of the subordinate old-wood component in the basin. We have carefully interpreted our findings in the context of this last assumption because samples of woody material collected from bars in the active channel of the adjacent Queets River (Fig. 1B) have returned radiocarbon ages ranging from modern to >1000 yr (Abbe and Montgomery, 1996b). Multiple ages from a single terrace deposit at a point and along the lateral extent of a mapped terrace provide an estimate of the degree of uncertainty in strath age.

Material used for 14C dating consists of detrital charcoal and wood as well as fir cones and decidual leaf matter. Care was taken to insure that the dated organic samples represented in situ, fluvially deposited materials associated with terrace aggradation, not the subsequent emplacement of organic matter by penetrating tree roots or weathering profiles. We report the 14C ages in both radiocarbon and calibrated calendar years before present (14C yr B.P. and A.D./B.C., respectively). The disparity between radiocarbon and calibrated ages is significant throughout the Holocene, and a single radiocarbon age can return more than one unique calibrated age. Multiple calibrated ages and variable standard errors can be reconciled by a summation of the normal distributions of individual calibrated 14C ages and their associated 1σ error (Ramsay, 2000). The result is a probability density plot of ages also used in similar studies of abundant radiocarbon dates (Meyer et al., 1995) or related normally distributed age data (Bull and Brandon, 1998). Coring representative red alders (Alnus rubra) at numerous localities provided an age for Qt7 (Wegmann, 1999).

We correlate terraces along the Clearwater valley by the map relationships, through deposit sedimentology and stratigraphy, and by considering general weathering characteristics such as relative soil development that we assume to be primarily influenced by the terrace’s relative age. It is important here to not introduce circularity in our methodology. Terrace correlation on age criteria alone assumes that a given terrace was more or less instantaneously created along its entire extent. Alternatively, a correlation based solely on the map relationships could potentially force terraces of very different age and genesis to be considered the same simply because it is extremely difficult to identify polygenetic straths or major unconformities in terrace deposits of similar sedimentology and texture. Given these concerns, we start with the mapped field relationships and allow the relative and numeric ages to help refine the correlation. The exercise is analogous to using biostratigraphy to transform lithostratigraphic units into chronostratigraphic units where time lines can be extended throughout the rock column. In our case, we wish to use the terraces as time lines along the river. Once properly correlated, we can measure the separation between a given strath level and the modern channel virtually anywhere in the drainage to obtain a point measurement of the rate of fluvial incision.

Vertical incision rates are determined from the separation between the dated Holocene straths and the valley-bottom strath, estimated by the low-water-level elevation during summer base-flow discharge. This is an appropriate datum from which to measure strath-height separation because it helps mark the reach-length average elevation of the valley-bottom strath and avoids measurements affected by local relief of the channel bed (Pazzaglia and Brandon, 2001). The separation between the terrace strath and valley-bottom strath was measured directly in the field with a tape measure, accurate to ±0.1 m for terrace straths <10 m above the channel or with an altimeter, accurate to ±1 m for terrace straths >10 m above the channel. We do not choose a single age for the straths based on numeric age data. Rather, we choose to calculate incision rates at points for which we have an uncalibrated radiocarbon numeric age. The age of the alluvium at that point is assigned to the age of the strath. We use the uncalibrated ages to avoid the complexity of multiple calibrated ages and their associated errors in the rate calculation. This approach allows us to observe regional trends in vertical incision without forcing circular reasoning upon when the strath was cut, when the alluvium was deposited, and when the strath was finally abandoned. Incision-rate errors are derived from the combined effects of 14C age standard errors, fluctuations in the elevation of the sum-
Figure 3. Longitudinal valley profiles of the Clearwater River and Holocene terraces. The profiles were produced by orthogonally projecting elevation data to a vertical plane oriented down the middle of the Clearwater Valley. Plot does not show terrace Qt7, which essentially lies on the valley’s long profile, or terrace Qt5/6, which cannot be clearly represented at this scale.

mer base-flow water level, and uncertainty in the measurement of the strath height, which includes both errors associated with the physical measuring of the strath height as well as variations in strath height along an outcrop face. The relative percentage of an incision rate error is greatest for the younger terraces and decreases with increasing terrace age and separation above the channel.

RESULTS

Channel and Longitudinal-Profile Characteristics

The lower 28 km of the Clearwater Valley is characterized by a mixed bedrock and alluvial channel that meanders across a 1–2-km-wide, low-relief valley. The alluvium, observed to be mobile during bankfull or higher discharges, has not been observed to be thicker than 2–3 m. Short (<100 m) but numerous stretches of bedrock are exposed in the channel bottom. Modern-channel gravel bars are transitory features that have changed significantly in recent time as shown by a comparison of gravel-bar location and size between 1990 aerial photographs and 1997–1998 field observations. The average valley gradient along this lower reach is 0.003 (Fig. 3). The upper reaches (above valley kilometer 28; Fig. 1C) of the Clearwater valley have a dominantly step-pool bedrock channel with short alluvial reaches concentrated at the junction of larger tributaries. Here, the average valley gradient steepens to 0.052 (Fig. 3).

The Clearwater channel bed is a flat-bottomed, low-relief unconformity cut across dipping bedrock. In the lower 10–15 km of the river valley (Fig. 1C), the channel bed extends laterally beneath the flood plain to the edges of the valley bottom where it is exposed by tributary streams that have incised through the flood plain (Fig. 2A). Farther upstream, the channel bed does not extend laterally to underlie what is easily recognizable on a topographic map as the valley bottom. Rather, it is clearly inset into a terrace strath (Fig. 2A) that in turn extends to the edges of what appears to be the valley bottom on a 7.5-minute quadrange map (see Fig. 8, cross section D–D’ of Pazzaglia and Brandon, 2001, for an illustration of this relationship). Separation between the channel bed and terrace straths increases upstream. Downstream they merge into the same unconformity (Fig. 3). Thus, we treat the modern channel bottom as the valley-bottom strath, exerting caution as to how far laterally we can project it under the flood plain, and use it as the datum to which we measure strath separation. The macrorelief on the valley-bottom strath is typically ~2 m, although there are some deep pools (~4 m), especially in meander-cutbank locations. We have endeavored to avoid these local deeps and focus more on reconstructing the average elevation of the valley-bottom strath for consecutive 500 m reaches of stream.

Fluvial terraces are best preserved in the reaches of the river characterized by a broad valley bottom and nonresistant mudstone and siltstone. Narrow bedrock reaches, and locally gorges, tend to correspond to outcrops of resistant medium- to thick-bedded, medium- to coarse-grained litharenite as well as pebble to cobbles conglomerate. In contrast, broader valley bottoms, and alluvial reaches, tend to be underlain by nonresistant, fractured, and thinly bedded mudstone and siltstone, as well as pervasively sheared rocks associated with the east-northeast–trending Clearwater River.
shear zone (Stewart, 1970). Distinct knickpoints in the upper part of the drainage confirm that all are coincident with resistant rock types. A broad convexity in the valley longitudinal profile around valley kilometer 25 (Fig. 1C) appears to be a persistent feature interpreted as being due to a fault or rising anticline (Fig. 3; Pazzaglia and Brandon, 2001).

We have observed features on the valley-bottom strath that lead us to consider both abrasion of the channel bed by coarse-bedload tools and plucking of weakened channel bedrock along joint and shear planes as likely mechanisms by which the channel incises vertically and laterally. The process of potholing, a common mechanism for channel-bed lowering on many bedrock streams (Whipple et al., 2000), does not appear to play a significant role in the Clearwater Channel, as potholes have been found only in the narrowest bedrock gorges where their formation and preservation are restricted to resistant pebble conglomerates.

**Terrace Stratigraphy and Map Distribution**

There are three distinct types of mappable terraces in the Clearwater basin: Fill, fill-cut, and strath (Bull, 1991; Fig. 4). Terraces Qt1, Qt2, and Qt3 (Pazzaglia and Brandon, 2001) are middle and late Pleistocene fill and fill-cut terraces found in mostly the middle to lower reaches of the basin. The thick alluvial fills of these Pleistocene terraces are consistent with major periods of valley aggradation during basin-wide, glacial cycle–driven changes in hydrology and sediment yield (Pazzaglia and Brandon, 2001).

Inset below the Pleistocene terraces are several well-preserved Holocene strath terraces (Qt4 through Qt7). These terraces are composed of a basal, 1–3-m-thick axial-channel coarse-gravel facies that is overlain by a 1–3-m-thick fine-sand and silt overbank facies (Fig. 2B). The channel gravel facies locally preserves sedimentary structures consistent with lateral accretion processes, such as might be expected for point and transverse bars. These bars and sediment of similar texture are present in the modern channel, so by analogy, we take the coarse-grained facies of the terrace deposit to represent the bedload being transported when the terrace strath was cut. In contrast, the fine-grained facies represents vertical accretion processes atop the flood plain that occur presumably during floods.

The Holocene terraces are both paired and unpaired and widely distributed, although there are some channel reaches devoid of terraces. In any ~500 m reach where the terraces are preserved, we can distinguish three major strath terraces—Qt4, Qt5, and Qt6—each vertically separated by at least 2 m of bedrock (Figs. 4, 5). Especially in the upper middle reaches of the river valley, we locally observe a strath between Qt5 and Qt6 designated Qt5/6. The youngest terrace, Qt7, has a more complicated morphology and distribution. In the lower reaches of the river (below valley kilometer 15; Fig. 1C) it is a fill-cut terrace cut into Qt6. Here both Qt6 and Qt7 share the same strath that is also coincident with the channel bed and valley-bottom strath. The treads of both Qt6 and Qt7 have been inundated by floodwaters during large historic floods. In the medial reaches of the valley (between valley kilometers 15 and 30; Figs. 1C and 5), Qt7 occupies its own strath that is coincident with the channel bed, both of which are clearly inset into the Qt6 strath. Here floodwaters inundate the Qt7 tread, but the Qt6 tread shows little evidence of floodwater inundation over the past several centuries. Farther upstream where the valley bottom narrows significantly, we do not recognize a Qt7. All Holocene terraces above Kunamaskt Creek (valley kilometer 35; location shown in Fig. 1C) are unpaired strath terraces cut either into bedrock or into an older (radiocarbon dead) alluvial-glacial valley fill of middle to late(?3) Pleistocene age. Locally, terrace deposits are buried by a tributary’s alluvial-fan deposits, which become more prevalent upstream of Kunamaskt Creek. Small unpaired late Holocene terraces with little lateral continuity may be associated with LWD jams in the upper 10 km of the channel (Fig. 1C). The correlation between these terraces and Qt6 and Qt7 is unclear.

The Holocene terraces are best preserved between valley kilometers 15 and 30 (Figs. 1C and 5), and we draw heavily upon this reach to understand the lateral extent and morphology of a given terrace. Here the valley bottom has narrowed to ~500 m, but the channel maintains an active meandering pattern. Qt5 tends to equal or exceed the width of the modern valley bottom evident on a 7.5-minute topographic map, whereas Qt6 is wholly confined to (and helps define) the modern valley bottom (Fig. 5). Mapping the terraces through this reach clearly demonstrates that the straths have a broad lateral extent. In some cases we
Figure 5. Map of river terraces in the medial part of the Clearwater Valley (modified from Wegmann, 1999). Letters following terrace names designations: a, b, c, d—treads that share a common strath; ipc—inset paleochannel. X–X’ is the location of the cross section shown in Figure 4.
are able to physically trace a strath and its overlying terrace deposit for hundreds of meters of nearly continuous exposure along the river bank. Uniform relative separation between the terrace strath and valley-bottom strath allows us to confidently project across reaches lacking exposure.

Holocene terrace deposits at the straths are of nearly uniform thickness. We could not discern any appreciable thickening or thinning of a given terrace. Rather, changes in thickness of the terrace deposits appear to be more closely related to the local relief on the terrace strath, the terrace location with respect to the valley-bottom edges, and the proximity to significant tributary streams. Terrace deposits are thinnest where exposed near the edge of the valley bottom and thickest immediately downstream of a major tributary. In summary, the geomorphic and sedimentologic characteristics observed in the modern channel—a mostly continuous mantle of uniform-thickness coarse-gravel beds and overbank fine-silt deposits atop a broad, laterally continuous, low-relief bedrock strath—is precisely what appears to be represented in the Holocene terrace deposits. We therefore assume that the modern channel and its deposits represent valley-bottom conditions throughout the Holocene.

**Terrace Age and Correlation**

Terrace ages are provided by 38 radiocarbon dates (35 AMS [accelerator mass spectrometry] and 3 standard beta-decay ages; Table 1). The radiocarbon dates reveal three broad age groupings on the probability density plot (Fig. 6). These three age groupings roughly correspond to three of the four mapped strath terraces Qt4, Qt5, and Qt6. The three age groupings are identified solely upon visual inspection of significant temporal breaks of ~600 and 1200 yr where we have no record of terrace alluvium. Figure 6 indicates that the alluvium overlying the Qt4 strath was deposited at ca. 11,000±9000 yr B.P. A paleochannel inset into the Qt4 tread strath was deposited at ca. 11,000±9000 yr B.P. We therefore assume that the modern channel and its deposits represent valley-bottom conditions throughout the Holocene.
tion of a given terrace, such as Qt5, is skewed toward younger ages (Fig. 6). The old tails on these distributions may mean that the strath was cut and alluvium with old wood was deposited immediately preceding strath abandonment. Alternatively, the skewed distributions mean that (1) alluvium overlaying the strath truly does have a large age range, and (2) there is more of the younger alluvium preserved at the expense of the older alluvium.

Rates and Distribution of Vertical Incision

We have extracted a subset of 25 uncalibrated radiocarbon dates to calculate point incision rates along the Clearwater long profile. Rates of vertical incision range from ~0.05–1 mm/yr in the lower third of the basin to ~1–2 mm/yr in the medial third, to ~2–3 mm/yr in the upper third (Fig. 7). Although similar in pattern to the incision documented for Pleistocene terraces (Pazzaglia and Brandon, 2001; Table 1), the rate of Holocene incision exceeds that calculated from the Pleistocene terraces by factors of two to three.

DISCUSSION

Conceptual Model for Strath-Terrace Genesis

The terrace data in the Clearwater basin are particularly well suited for considering various models of strath-terrace genesis in the tectonically active setting. The Clearwater River is incising because the Cascadia forearc high continues to rise. If the rate of river incision perfectly matched that of the uplifting rocks and if the river responded to no other external forces including base-level changes or watershed hydrology, the river might be expected to leave an incomplete, disjointed suite of unpaired strath terraces similar to those envisioned by Bull (1990) or Merritts et al. (1994) and modeled by Hasbargen and Paola (2000). Under these conditions, it is a “random” component of fluvial incision into bedrock that fortuitously leads to the preservation of a strath terrace. Our data are not consistent with this type of strath-terrace record, so we must appeal to other conceptual models for strath-terrace genesis that are decidedly more deterministic, such as those modeled by Hancock and Anderson (2001).

We quickly dispense with the possibility that the terraces are formed by logjams of LWD (Montgomery et al., 1996; Abbe and Montgomery, 1996a, 1996b). Prior to large-scale logging in the upper Clearwater watershed, the main-stem Clearwater channel did not contain numerous logjams (J. Cederholm, 2001, personal commun.), contrary to observations in the adjacent Queets River. We have not observed the sedimentary textures or deposit morphologies associated with terraces or ponded deposits behind LWD dams in the Clearwater River. We know of no location in the lower and middle reaches of the basin where a large concentration of jumbled woody debris representing paleo-log jams are preserved. In summary, we do not dispute the presence of log-jam terraces in the prehistoric Clearwater River. But we do question the likelihood of preserving these features as the terraces we have found and mapped.

A more likely possibility for Holocene terrace genesis is a downstream fall in base level and the subsequent upstream migration of one or more knickpoints. This is an appealing model because it has been used to explain late Pleistocene and Holocene terraces described for small, steep mountainous drainages of the Oregon and northern California Coast Ranges that empty directly into the sea (Seidl and Dietrich, 1992; Merritts et al., 1994). But for the Clearwater River, we can find no compelling evidence that the mapped terraces project upstream into knickpoints or knickzones (we use the term knickzone to describe kilometer-scale channel reaches where the change in channel gradient is expressed across a broad convexity; see Zaprowski et al., 2001) (Fig. 3). Nor
can we demonstrate that a given terrace strath, terrace alluvium systematically youngs upstream as it should if it is related to a headward-propagating knickpoint. All of the terraces investigated in this study are Holocene in age, so we cannot call upon dramatic falls in sea level to even initiate the upstream march of a knickpoint, unless the knickpoints were created prior to the Holocene during Pleistocene eustatic lows. If that was the case, the long time periods represented by the relatively slowly retreating knickpoints should be immediately apparent in time-transgressive terrace deposits, which we do not observe. Furthermore, the slow steady rise of Holocene sea level has produced a relative base level rise for the Clearwater River that should be accommodated by channel stability or aggradation rather than incision, which we also do not observe (Bull, 1991). It is possible that relative falls in base level are created by a rate of rock uplift at the coast that has outstripped the corresponding rise of sea level in the Holocene. But more rapid fluvial incision upstream rather than downstream, preservation of Pleistocene deposits at sea level (Pazzaglia and Brandon, 2001), and low amounts of unroofed section at the coast (Brandon et al., 1998) together do not favor this possibility. Instantaneous falls in base level attributed to rupture on faults remains a option, and there are some field relationships near valley kilometer 25 supportive of active faulting (Figs. 1C and 5); however, the general continuity of the straths and uniform thickness of terrace deposits make it difficult for us to link genesis to such poorly defined faults (Wegmann, 1999).

The apparent lack of obvious base-level control on terrace genesis brings us to consider a river with a variable rate of both lateral and vertical incision modulated by changes in watershed hydrology and sediment yield (Meyer et al., 1995). This general model is supported by the map distribution of terrace deposits (Fig. 5), their stratigraphy and morphology (Fig. 4), and numeric age (Fig. 6, Table 1). The model holds that the Clearwater River alternates between phases dominated by lateral incision, valley-bottom widening, and the carving of straths balanced by phases of vertical incision, valley-bottom narrowing, and limited strath cutting (Fig. 8).

We consider the possibility that the strath and alluvial deposit are genetically related, that is, the ages of the terrace alluvium estimate the times of enhanced lateral corrosion and valley-bottom widening (Gilbert, 1877; Mackin, 1937; Fig. 8, case A). For example, a lateral corrosion phase represented by the Qt5 terrace would span ~4000 yr. During that time, the channel would sweep laterally, carve the strath, and temporarily store alluvium in the flood plain. Progressive lateral sweeps of the channel would tend to remove previously deposited alluvium, leaving behind new, younger alluvium in its place. Assuming that the alluvial thickness above the valley-bottom strath is equal to the active layer as we infer to be the case during periods of strath cutting, there should be a disproportionately large amount of alluvium in the flood plain that immediately precedes strath abandonment and only a fragmented record of older alluvium marking the onset and duration of strath cutting. The skewed age distributions support this idea: the highest frequency of ages are skewed toward the younger side of the distribution (Figs. 6 and 8). The time periods marked by the complete lack of any dated terrace alluvium indicate one of two possibilities. First, these may simply be times when the river was not carving laterally and leaving an alluvial record atop straths, but rather was narrowing its valley bottom, as the river mainly incises vertically. Alternatively, the river always maintained a component of lateral corrosion and formed terraces, but these terraces were subsequently destroyed by a younger, major valley-bottom widening event. In this case, a younger terrace is inset into the valley at the removal and expense of one or more older terraces. The very fragmentary record of Qt4 may be the result of this process. The prolonged period of valley-bottom widening and strath cutting represented by Qt5 may have simply cut out most of the Qt4 record.

An alternative way of interpreting Figures 6 and 8 is to consider that there are discrete phases of strath cutting, followed by alluvial aggradation above the strath, and then vertical incision (Fig. 8, case B). This is the same model generally applicable to terraces produced during glacial-interglacial changes (Bull, 1991) and one that appears to match the data for the Pleistocene terraces in the Clearwater basin (Pazzaglia and Brandon, 2001). In this case, the straths would be cut during the temporal breaks in the summed probability distribution (Figs. 6 and 8, case B). In this model, the times of valley-bottom widening are relatively short, and the times of alluvial aggradation atop the straths are long, spanning the time represented by the range of radiocarbon ages. At one locality we may have insights into the time span represented by alluviation atop the strath. Three samples collected in a vertical profile in Qt6 returned ages of 1935 ± 53 14 C yr B.P. (A.D. 0–130; AA26662) for the base of the channel-gravel facies, 929 ± 41 14 C yr B.P. (A.D. 1030–1160; AA26664) in the middle of the channel-gravel facies, and 373 ± 40 14 C yr B.P. (A.D. 1440–1640; AA26665) (outer ring of a rooted tree stump) for the overbank facies. We have no way to unequivocally interpret these stratigraphically consistent ages in the context of old wood endemic to the setting and stress that
these data simply provide some typically difficult-to-obtain insight. Taken at face value, they would suggest a phase of Qt6 terrace formation over an approximate 2000-yr time span.

An important limitation on these two alternatives concepts of when the straths are cut lies in the rates of lateral corrosion the channel might achieve in carving out a strath. By “lateral corrosion” we refer to any process that causes the channel to sweep laterally. These processes include lateral translation of the channel to increase the meander amplitude, sometimes called meander swing, as well as the down-valley sweep of meander loops. In Figure 5, both the width and meander wavelength for the Qt5 strath is ~500 m. If the strath and terrace deposit are genetically related and if the Qt5 alluvium spans ~4000 yr, then the channel is able to sweep laterally at a rate of 12.5 cm/yr. This is a relatively fast rate for a bedrock-corrosion process, but not to mention the fact that ~2 vertical meters of rock must also be consumed during the lateral incision to inset Qt5 below Qt4. If, on the other hand, the straths are cut in the short time periods between the dated alluvium, the rate of lateral corrosion needed to carve out the Qt5 strath is ~83 cm/yr, approaching what may be an unreasonably rapid rate for a bedrock-corrosion process. Nevertheless, published rates of meander swing and sweep of semiarid alluvial channels are as high as 400 and 800 cm/yr, respectively (Wells et al., 1982). Where lateral incision involves the carving of bedrock, the rates are almost certainly slower. The simplest way to maximize the time necessary to laterally carve out wide straths is to assume that the strath cutting and overlying alluvium are genetically related and contemporaneous as we have alluded to throughout this paper (Fig. 8, case A). In this case, the age of the youngest alluvium closely dates abandonment of the strath. When mapped correctly, the strath can be used to measure the rate of vertical incision anywhere along the river where the strath is preserved, but may be lacking a numeric age date in the overlying alluvium.

We propose that the Clearwater channel, currently in a mode of minor valley widening and alluviation, “normally” rests at or slightly below capacity. A decrease in sediment flux to the channel will drop the channel below capacity and foster valley-bottom narrowing and vertical incision in the manner envisioned by Meyer et al. (1995) and Sklar and Dietrich (1998) (Fig. 8). Valley-bottom narrowing, essentially a reduction in the meander amplitude, allows a river with a decreased amount of abrasive tools to attain the gradient or capacity necessary to maintain incision opposing the rate of rock uplift. Indeed, the alluvium is critical to both lateral and vertical abraskation processes (Foley, 1980; Slingerland et al., 1997; Sklar and Dietrich, 1998). In contrast, terraces record a time of increased sediment flux from hillslopes throughout the basin when the channel is pushed slightly over capacity, the meander amplitude increases, the process of lateral corrosion is maximized, and the valley bottom widens.

**Possible Causes of the Variation in Sediment Flux to the Channel**

The Holocene terraces along the Clearwater River suggest a delicate balancing act between the delivery of sediment from the hillslopes and corresponding channel response. The variations in hillslope sediment flux cannot be so great as to completely cause the valley to aggrade, as the terraces older than Qt4 indicate happened in the late Pleistocene. The terragenesis model calls for an investigation of possible triggers for altering the hillslope sediment flux.

Hillslopes that have been destabilized by a change in climate and vegetation are the most likely, often-cited sources of a temporally variable sediment flux (Reneau et al., 1989, 1990; Reneau and Dietrich, 1991; Bull, 1991; Meyer et al., 1995; Pederson et al., 2000, 2001). Several studies in Cascadia appeal to this model to explain the widespread preservation of a ca. 10 ka strath terrace formed during the stripping of hillslope sediment at the late Pleistocene–Holocene climatic boundary (Merritts et al., 1994; Personius, 1995; Massong, 1998). Qt4 may represent the late Pleistocene–Holocene climate transition terrace in the Clearwater basin. The explanation as to why this terrace is spatially insignificant in the Clearwater basin when compared to other similarly sized basins in Cascadia is not clear. It is possible that valley-bottom widening and strath cutting during the middle Holocene, leading to the subsequent genesis of Qt5, removed most of the evidence for the earlier late Pleistocene to Holocene transition terrace.

Global (Bond et al., 1997) and local (Huesser, 1974, 1977, 1978, 1983; Worona and Whitlock, 1995; Gavin et al., 2001) late Pleistocene and Holocene paleoclimate reconstructions provide permissive, but by no means unequivocal explanations for variable hillslope sediment fluxes in the Clearwater basin. For example, Bond et al. (1997) argued for climatic oscillations at ca. 8500, 5000–3000 and 2000–100 yr B.P. and Pisias et al. (2001) recognize similar millennial scale climatic variability in the Pacific Northwest. We note that these dates are roughly coincident with the gaps in our terrace ages. Unfortunately, this favorable coincidence is obscured by detailed, local palynological studies that seem to indicate a major climatic shift to drier conditions at the late Pleistocene–Holocene boundary followed by a gradual shift to more wet (marine?) modern conditions beginning ~3000 yr ago. The latter shift is not particularly abrupt, highly variable, and evidence for it is locally absent from a core taken at Yahoo Lake (Fig. 1C), within the Clearwater basin (Brubaker, 1998, personal commun.; Gavin et al., 2001). Nevertheless, late Pleistocene and Holocene climate change is a favored explanation for triggering the episodic liberation of sediment from hillslopes throughout the Coast Ranges (Reneau et al., 1989, 1991; Reneau and Dietrich, 1991; Personius et al., 1993). In particular, Reneau et al. (1989) and Reneau and Dietrich (1991) documented a ca. 7–4 ka evacuation of colluvial hollows that is more or less coincident with the Qt5 terrace alluvium. These studies suggest that the residence time for regolith on Olympic Peninsula hillslopes is about 5–6 k.y. and its liberation is primarily limited by the rate of its in-situ production working in concert with climate change, rather than the magnitude of climate change alone. The landscape must be first primed and ready to respond before a trigger can cause sediment to be liberated from the hillslopes and delivered to the channel.

Any discussion of potential triggers that might liberate sediment from hillslopes leads us to consider the role of earthquakes (Keefer, 1981; Shimazu and Oguchi, 1996; Hovius et al., 1999; Hovius, 2000; Densmore and Hovius, 2000) in this seismically active setting. We are drawn to the large body of research that has demonstrated the recurrence (~500–3000 yr) of large-magnitude (M 8 or greater) earthquakes associated with slip on the subducting Juan de Fuca slab (Atwater and Hemphill-Haley, 1997). Also potentially important are the earthquakes that originate in the upper plate, such as those attributed to the Seattle fault rupture ~1000 yr ago (Bucknam et al., 1992; Johnson et al., 1994, 1999). The geomorphic events triggered include tsunamis and coastal uplift and/or subsidence in Puget Sound (Atwater and Moore, 1992; Bucknam et al., 1992), large-scale rock avalanches on the Olympic Peninsula (Schuster et al., 1992), and major landslides into Lakes Washington and Samamish (Karlin and Abella, 1992; Jacoby et al., 1992; Logan et al., 1998). Although we are hesitant to place too much emphasis on age coincidence, the liberation of
sediment during this, or similar upper-plate earthquakes, may have contributed to the alluvium that was ultimately incorporated into Qt6. If having to wait until a landscape is primed with enough regolith is the true rate-limiting factor (Reneau and Dietrich, 1991), then earthquakes are as viable a trigger as climate change. Furthermore, it may be that different components of a given landscape respond to different sediment-liberating triggers; for example, colluvial hollows may preferentially respond to climatically induced changes in hillslope vegetative communities, whereas large-scale deep-seated bedrock landslides may respond more frequently to seismic triggers. In both cases (climate or earthquakes), it is the same general coincidence of ages between the trigger and the response that appeals to the geomorphologist. The earthquake trigger explanation suffers from the fact that earthquakes are ubiquitous throughout the Holocene; it would be virtually impossible with the range of radiocarbon dates to convincingly appeal to a single earthquake as the cause of a river terrace. Likewise, the climate argument suffers from an underwhelming documentation of Holocene vegetative response within the Clearwater basin, a response that we might expect if climate change is forcing hillslope-sediment liberation, as is documented for periods of colluvial-hollow excavation in central California (Reneau et al., 1990).

**Comparison of Holocene to Pleistocene Rates of Incision**

The rates of river incision determined from Holocene terraces increase in the upstream direction, similar to the rates determined from Pleistocene terraces (Pazzaglia and Brandon, 2001; Fig. 7). However, the Holocene incision rates are everywhere more rapid than their corresponding Pleistocene incision rates. Some studies have pointed out the apparent bias that may result from measuring rapid geologic and geomorphic rates with data collected over a short rather than long time span (Gardner et al., 1987; Mills, 2000). Mills (2000) has suggested that an increase in the rates of river incision is real and can be directly attributed to the fluvial response to a progressively cooler climate characterized by glacial-interglacial cycles. The terraces of the Clearwater basin do not readily lend themselves to that particular explanation because they cover such a limited time span across the late Pleistocene and Holocene.

One way to reconcile the differences in incision rate without having to invoke recent increases in the rate of rock uplift is to consider the general differences between the Holocene and Pleistocene Clearwater River. With respect to the Pleistocene river, the Holocene Clearwater River is a stream that is mostly at capacity. It is well equipped with just the right amount of abrasive tools to accomplish incision of its valley bottom in the face of tectonic processes that continue to advect rocks upward through its channel bed. Subtle deviations from this condition foster the variations in the degree of accompanying lateral incision that make and preserve strath terraces. In contrast, the Pleistocene Clearwater River was a stream that, during significant periods of time, was above capacity. During these periods, the channel was lifted completely off the strath, vertical incision ceased because the river and its abrasive tools were no longer in contact with the bedrock of the valley bottom, and the stream flowed as an alluvial channel. There was no headway made on consuming the rock uplifted beneath the channel bed by tectonic processes when the river was in this aggradational phase. The river profile gradient was certainly steepened, and its concavity may have been reduced as uplift continued beneath the valley bottom. It is only during interglacial periods like the Holocene, with at- or near-capacity sediment-transport conditions, that the long-profile gradient can be reduced and concavity possibly increased as the river makes up for time lost to vertical incision during the alluvial phase. During the Holocene, the Clearwater River is again carving into the bedrock at rates equal to or faster than the rate of rock uplift (Figs. 7, 8). These arguments suggest that geomorphic and active tectonic investigations can only extract meaningful rates of rock uplift from incising streams if the measured incision is integrated across at least one glacial-interglacial cycle.

**CONCLUSIONS**

The ~400 km² Clearwater basin, located on the western flank of the actively uplifting Olympic Mountains, contains a well-preserved flight of Holocene fluvial terraces. The Clearwater River is a mixed bedrock and alluvial stream that becomes progressively more influenced by bedrock in the steep, upper one-third of its drainage. Field mapping demonstrates three major and two minor Holocene strath terraces within the lower two-thirds of the 52-km-long river. The three major Holocene terraces are characterized by nearly horizontal straths carved across steeply dipping bedrock; the straths are similar in width to, or wider than, the 0.25–0.5-km-wide modern valley bottom. The terrace deposits atop these straths consist of ~2 m of coarse sand and gravel conformably overlain by ~1 m of fine-sand and silt overbank deposits. This sedimentology is consistent with that observed for sediment in the active Clearwater channel and on the flood plain. The terraces are laterally continuous for hundreds of meters. Field relationships could not convincingly determine that the terraces converge or project up stream into channel knickpoints, nor could they argue for down-stream thickening of terrace deposits against dams of LWD. When converted to calendar ages and accounting for 1σ errors, the terrace ages, determined by 38 14C dates (Table 1), fall into three main groups of ca. 11,000–9000 yr B.P., 8000–4000 yr B.P., and 3000–0 yr B.P., corresponding to terraces Qt4, Qt5, and Qt6, respectively (Fig. 6). These thin Holocene strath terraces stand in marked contrast to thick Pleistocene fill terraces that indicate that the Clearwater Valley was alternately backfilled and then evacuated of thick alluvial sediments. The map relationships, sedimentology, and ages of the terraces allow us to summarize the following interpretations:

1. The Holocene fluvial-terrace stratigraphy of the Clearwater River basin in western Washington State is somewhat different from other, similarly studied basins in Cascadia. Namely, similar studies (e.g., Personius et al., 1993; Merritts et al., 1994; Massong, 1998) have emphasized the presence of a widespread late Pleistocene–early Holocene terrace genetically linked to the well-documented climate change across that boundary. Qt4 in the Clearwater basin is likely representative of the late Pleistocene–Holocene terrace, but its preservation is much subordinate to the middle and late Holocene terraces Qt5 and Qt6. The lack of a well-preserved and widespread late Pleistocene–early Holocene terrace may indicate different climatic conditions for northern Cascadia at this time with respect to Oregon or California, or it may suggest that lateral incision and valley widening related to the Qt5 event were efficient at removing the older terrace.

2. The favored model for genesis of Holocene-scale terraces within the Clearwater basin involves a channel with a temporally variable rate of both lateral and vertical incision. The terraces represent times of enhanced lateral incision, valley-bottom widening, and the carving of straths accomplished by the thin alluvial deposits preserved atop the straths for >2–4000 yr (Fig. 8, option A). The frequency distributions of the ages of the terrace deposits overlying a given strath support this idea because the distributions are skewed toward the
younger extreme of the entire age range (Figs. 6, 8). Valley-bottom narrowing and rapid vertical incision into bedrock were accomplished during the relatively brief (∼1000 yr) time periods between the carving of the major straths.

3. We envision the Holocene Clearwater River as operating at or near capacity. The alternations in rates of vertical and lateral incision may be linked to temporal variations in the liberation and delivery of hillslope sediment to the Clearwater channel that affect the at-capacity condition. Times of increased hillslope sediment flux favor lateral incision, especially if those times coincided with stable, steady discharges like those envisioned for the valley-bottom widening cycles described in Meyer et al. (1995). Similarly and following the same analogy, a reduction in the sediment yield, especially in concert with a flashier discharge, fosters valley-bottom narrowing and vertical incision. Holocene climate change is an unknown factor in driving these changes in hillslope sediment yield, in part because of the lack of convincing, local, high-resolution proxy records. We appeal to the possibility that ground accelerations associated with earthquakes could be a viable alternative mechanism for liberating hillslope sediment when slope-moisture conditions were favorable to slope failure and/or when the slopes were primed with a sufficient thickness of regolith awaiting a trigger to liberate it. In a way analogous to how frequent large fires in the intermontane west are only effective at destabilizing hillslopes if they happen to occur during relatively dry climates with highly seasonally precipitation (Meyer et al., 1995), the earthquakes might only be effective when some other condition, like soil moisture and/or adequate regolith thickness, is present.

4. Rates of vertical fluvial incision, determined from Holocene terraces, are similar to the rates determined from Pleistocene terraces (Pazzaglia and Brandon, 2001) in that they are relatively low downstream and progressively increase in an upstream direction, subparallel to the direction of plate convergence (Fig. 7). However, the Holocene incision rates are everywhere more rapid (2–3 times) than their corresponding Pleistocene incision rates of <0.1 m/k.y. at the coast to 0.9 m/k.y. in the upper Clearwater basin; the Pleistocene incision rates more closely approximate the long-term rates of orogen unroofing determined from thermochronology (Brandon et al., 1998). We favor an explanation in which the Holocene rates represent a channel rapidly reacquiring its stable, graded concavity following protracted periods of time in the Pleistocene when it could not accomplish any vertical incision into bedrock because the channel was lifted off the bedrock-valley bottom by climatically induced alluviation. These results illustrate how even in tectonically active settings, representative rates of rock uplift inferred from studies of river incision should be temporally integrated over at least one glacial-interglacial cycle.

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