Valley formation by fluvial and glacial erosion

David R. Montgomery
Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195, USA

ABSTRACT

Cross-valley profiles from the west slope of the Olympic Peninsula, Washington, are used to investigate the relative effects of fluvial and glacial erosion on valley formation. Unlike most ranges where glaciers and rivers sequentially occupied the same valleys, neighboring valleys in the Olympic Mountains developed in similar lithologies but were subject to different degrees of glaciation, allowing comparison of the net effect of glacial and fluvial processes integrated over many glacial cycles. Upslope drainage area was used to normalize comparisons of valley width, ridge-crest-to-valley-bottom relief, and valley cross-sectional area as measures of net differences in the mass of rock excavated from below ridgelines for 131 valley-spanning transects. Valley width, relief, and cross-sectional areas are similar for glaciated, partly glaciated, and unglaciated (fluvial) valleys with drainage areas of $<$10 km^2, but diverge downslope. Glaciated valleys draining $>$50 km^2 reach two to four times the cross-sectional area and have to 500 m greater relief than comparable fluvial valleys; partly glaciated valleys have intermediate dimensions. At distances of $>$5 km from valley heads, the cumulative upstream volume of rock removed to form valleys is two to four times greater in glacially incised valleys than in fluvial valleys. The finding of strong differences in the net result of valley excavation by fluvial and glacial erosion supports the interpretation that alpine glaciers are more effective erosional agents than are rivers and implies that large alpine valleys deepened and enlarged in response to Pleistocene glaciation.

Keywords: glacial, fluvial, erosion, valley formation.

INTRODUCTION

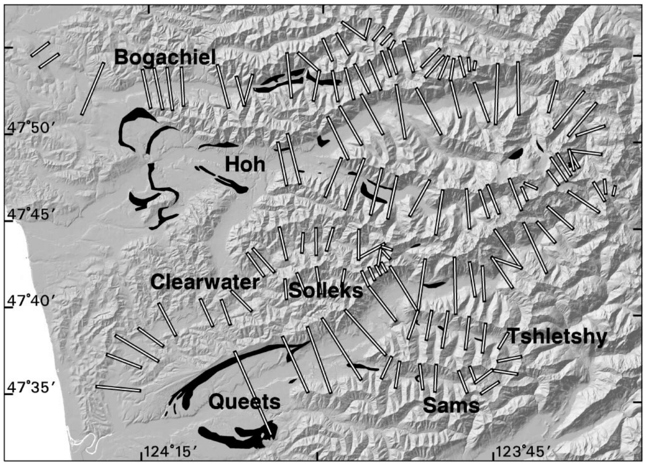
There is no longer serious debate about whether glaciers can erode their beds and sculpt topography, but debate continues over whether glaciers are more erosive than rivers. Some workers find evidence for greater rates of glacial erosion than fluvial erosion (e.g., Clague, 1986; Braun, 1989; Harbor and Warburton, 1992, 1993; Clayton, 1996; Hallet et al., 1996; Kirkbride and Mathews, 1997), whereas others find evidence for low rates of glacial erosion or little difference between fluvial and glacial erosion rates (e.g., Sugden, 1976, 1978; Lindström, 1988; Hicks et al., 1990; Summerfield and Kirkbride, 1992; Hebdon et al., 1997; Lidmar-Bergström, 1997). However, comparisons of fluvial and glacial erosion rates face the fundamental problem that glaciers and rivers sequentially occupied the same valleys, making the signatures of glacial and fluvial processes on valley size difficult to deconvolve (Roberts and Rood, 1984). Global comparisons are further complicated by the fact that data come from widely different settings, such as cold-based continental ice sheets, warm-based alpine glaciers, and temperate, tropical, and arid rivers in a broad range of tectonic contexts. Although the most comprehensive comparison indicates that sediment yields are higher in glaciated than in unglaciated regions (Hallet et al., 1996), recent studies in areas of rapid uplift document river incision rates comparable to high erosion rates in glaciated regions (e.g., Burbank et al., 1996). Moreover, sediment yield data are difficult to translate directly into erosion rates owing to long-term sediment storage in fluvial systems (Dunne et al., 1998; Goodbred and Keuhl, 1998) and the potential for lag times between erosion and sediment delivery to exceed the duration of typical glacial cycles (Church and Slaymaker, 1989).

Of central importance to understanding feedback among climate change, erosion, and tectonics in alpine areas is whether glaciation leads to more erosion and greater relief than can be attributed to fluvial processes. Whipple et al. (1999) analyzed river longitudinal profiles and argued that any influence of higher erosion rates in glacial periods is likely to have only limited impact on relief for equilibrium river profiles in mountain systems where development of threshold bedrock slopes prevents attainment of steeper valley sides (Schmidt and Montgomery, 1995). Physically based models have been proposed for the development of U-shaped glacial valley forms from initially V-shaped fluvial valleys (Harbor et al., 1988; Hirano and Aniya, 1988; Harbor, 1992), and the influence of rock strength on glacial valley form also has been investigated (Augustinus, 1992b), but there has been no direct quantitative comparison of valley morphology in comparable glaciated and unglaciated basins. Here I report evidence for substantial differences in the geomorphic expression of fluvial and glacial erosion in the Olympic Mountains, Washington.

STUDY AREA

The Olympic Mountains of western Washington comprise an accretionary wedge that rose from the Pacific Ocean in the late Miocene in response to convergence of the Juan de Fuca plate and North America (Tabor and Cady, 1978). Rock-uplift rates across the range have been steady since ca. 14 Ma, and the range is thought to have been in topographic steady state for most of that time (Brandon et al., 1998). The Olympic Mountains are just south of the maximum extent of Pleistocene ice sheets but were the site of repeated episodes of alpine glaciation. Geologic mapping of the western Olympics shows that some valleys in the range repeatedly hosted large Pleistocene valley glaciers, whereas others had either no glaciers or smaller glaciers generally restricted to their headwaters (Washington Division of Geology and Earth Resources Staff, 2001). The west side of the Olympic Mountains presents an unusual opportunity in that a series of neighboring val-

Figure 1. Shaded relief map of west slope of Olympic Mountains, Washington, showing locations of basins studied, cross sections (white bars), and moraines (black areas) as portrayed on 1:100 000 scale geologic maps (Washington Division of Geology and Earth Resources Staff, 2001).



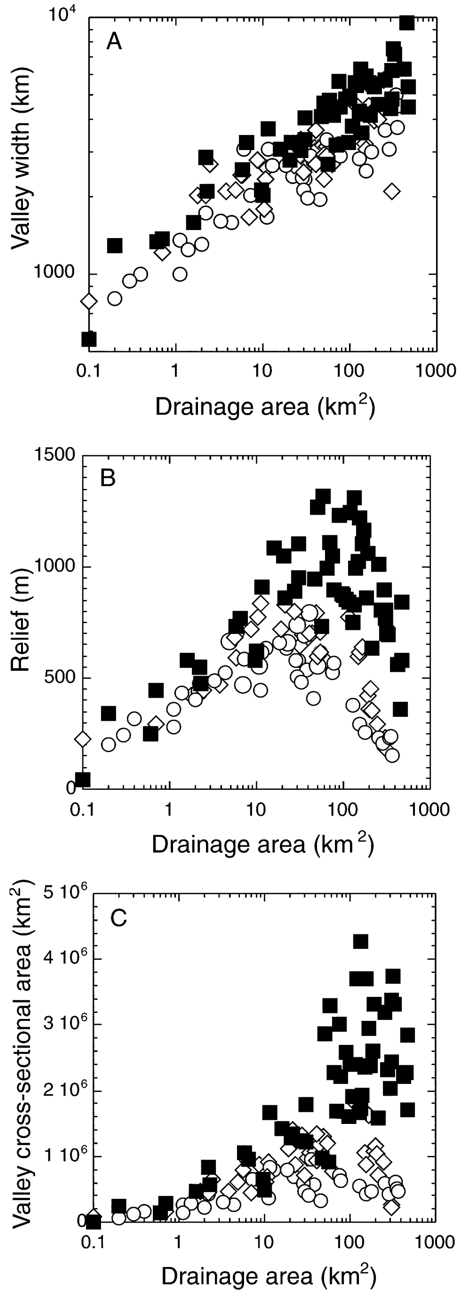


Figure 2. Comparison of valley morphometry vs. drainage area for (A) valley width; (B) ridge-crest-to-valley-bottom relief; and (C) valley cross-sectional area. Black squares represent valleys with major alpine glaciers (Hoh, South Fork Hoh, and Queets), triangles represent partly glaciated valleys (Bogachiel, Tshletshy, and Sams), and circles represent unglaciated fluvial valleys (Clearwater, North Fork Bogachiel, and Solleks).

leys with similar geology had strikingly different glacial histories but shared the same general climate variability through time. As the range has been in a topographic steady state since the late Miocene, a well-developed fluvial valley network must have evolved prior to onset of Pleistocene glaciation, which modified an initial fluvially incised valley network. River systems exhibit systematic scaling in which channel and valley size increase with drainage area or river discharge (Leopold and Maddock, 1953), and fjord size similarly scales with drainage area or ice discharge (Roberts and Rood, 1984; Augustinus, 1992a). Such relationships suggest that systematic differences in the morphometry of valleys on the western slope of the Olympic Peninsula between those formed primarily by fluvial erosion and those sequentially incised by both glacial and fluvial erosion can be used to gauge long-term morphologic effects of glaciation on valley form.

METHODS

The spatial distribution of glacial moraines was used to assess the relative degree of glacial influence on nine valleys (Fig. 1). Fully glaciated valleys (Hoh, South Fork Hoh, and Queets) had large, valley-spanning Fraser and pre-Fraser age moraines. Partially glaciated valleys (Bogachiel, Sams, and Tshletshy) had less extensive glacial influences with small Fraser age moraines located partway down the valley. Unglaciated valleys had no mapped moraines (Clearwater, North Fork Bogachiel, and Solleks). A total of 131 valley-spanning, ridgetop-to-ridgetop cross sections were derived from a 10-m-grid digital elevation model (DEM) compiled for the range; 54 transects were from fully glaciated basins, 42 were from partially glaciated basins, and 35 were from unglaciated basins. Cross sections were oriented orthogonal to the valley centerline and located to avoid the complicating influence of tributary valleys. In addition, data were limited to drainage areas of 0.1 km^2 to 500 km^2, because finer scale features are not well resolved and glaciers did not extend much beyond this range in valley size.

Comparisons of valley morphometry were normalized by the drainage area upslope of each cross section. Mean slope and precipitation also were calculated for the drainage basin upslope of each cross section. Valleys that head highest in the range developed large valley glaciers in the glacial climate, but the dominantly fluvial valleys on the western slope of the Olympic Mountains also extend to high elevations where precipitation reaches 4–5 m·yr^{-1}. Modern drainage divides do not necessarily coincide with Pleistocene ice divides, but the two should be similar in the high-relief valleys in the core of the range, and any glacial spillover would account for a progressively smaller proportion of the drainage area downstream through the valley network. The relief given by the difference between the present maximum and minimum elevations on each valley-spanning topographic cross section provides only a minimum constraint on the local bedrock relief, because postglacial alluvial valley fills now occupy valley floors. The methodology I employ does not evaluate erosion rates directly, but allows assessment of the integrated long-term signature of erosional processes on the volume of material removed from between valley walls. Hence the approach allows examination of the relative efficacy of fluvial and glacial processes as valley-forming agents.

RESULTS

Valleys carved by alpine glaciers on the western slope of the Olympic Mountains are generally wider than fluvially carved valleys, although the difference is less clear at small drainage areas (Fig. 2A). The width of glaciated valleys increases faster downslope than the width of fluvial valleys such that at drainage areas of >10 km^2, glacial valleys are as much as twice as wide as fluvial valleys. This greater cross-valley ridge-to-ridge distance indicates valley excavation well beyond that expected to result simply from conversion of an initially V-shaped valley to a U-shaped valley, which can be done with no change in overall valley width (Harbor et al., 1988; Harbor, 1992).

Ridge-crest-to-valley-bottom relief for all three types of valley initially increases at low drainage areas and then decreases at higher drainage areas (Fig. 2B). There is little difference in the relief of fluvial and glacial valleys for drainage areas of <10 km². At larger drainage areas, the relief of glacial valleys progressively exceeds that of fluvial valleys; differences in relief increase to ~500 m for drainage areas of >50 km². The drainage area associated with the maximum cross-valley relief is offset, with glacial overdeepening extending farther downslope than the maximum local relief in fluvial valleys. Hence, the greatest relief enhancement by alpine glaciers is focused significantly downvalley from glacier source areas.

The cross-sectional areas of glaciated, partly glaciated, and fluvial valleys vary within about a factor of 2 around their underlying trends (Fig. 2C). Although cross-sectional areas of glaciated valleys are comparable to those of fluvial valleys at drainage areas of <10 km², the difference increases to two to four times for drainage areas of >50 km². Hence, there is little difference in the amount of material differentially eroded to form valleys between fluvial and glacial valleys for small drainage areas at high elevation, but differences between the two valley types increase dramatically for larger drainage areas.

The cumulative upstream volume of rock removed to form valleys (determined from the valley cross-sectional area and the distance downvalley between successive cross sections) is substantially different for fluvial and glacial valleys (Fig. 3). At distances of <5 km from the valley head there is no compelling difference, but at greater distances downvalley, the cumulative valley volume increases much more rapidly for glaciated valleys than for fluvial valleys, and partly glaciated valleys are intermediate. At distances of >10 km from valley heads, glaciated valleys represent net removal of two to four times the mass of rock than fluvial valleys.

Mean basin slope varies by only a few degrees between the three types of valleys for basins >10 km² (Fig. 4). The headwaters of two of the glaciated valleys (Hoh and South Fork Hoh) receive substantially more precipitation than the other valleys (including the glaciated Queets). However, in basins with a drainage area of 100 km² the mean basin precipitation for fluvial and partly glaciated valleys ranges from 77% to 97% and from 86% to 104%, respectively, of the values for glaciated valleys.

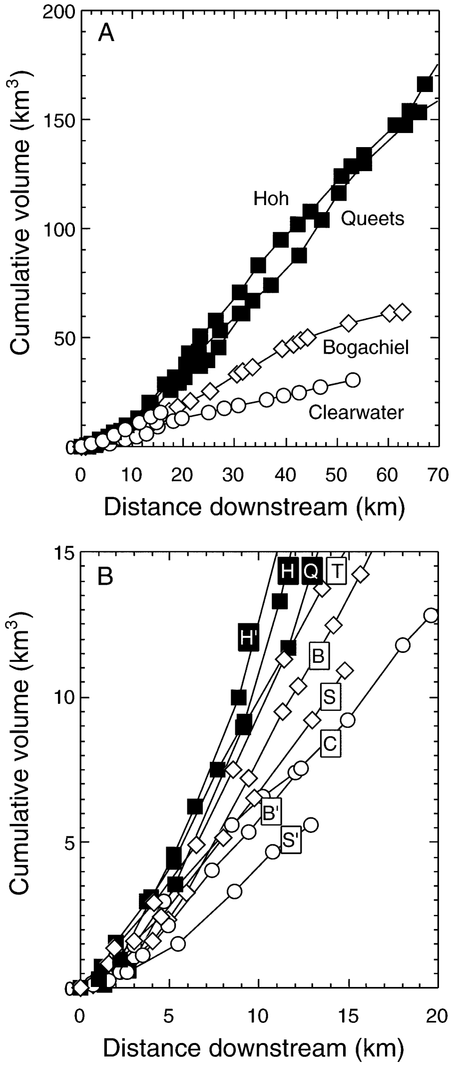


Figure 3. A: Cumulative volume of rock removed from upstream to form valley as function of distance down valley. B: Enlargement of uppermost 20 km of each valley system. H—Hoh, H′—South Fork Hoh, Q—Queets, T—Tshletshy, B—Bogachiel, S—Sams, C—Clearwater, B′—North Fork Bogachiel, and S′—Solleks. Black squares—glaciated valleys; triangles—partially glaciated valleys; circles—unglaciated fluvial valleys.

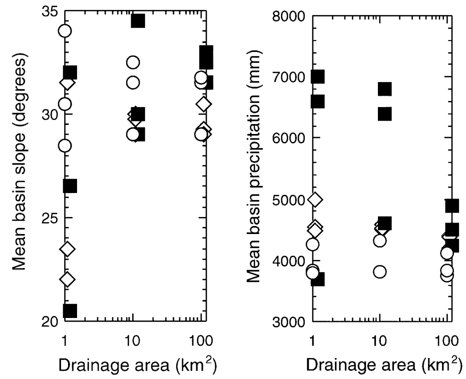


Figure 4. Mean basin slope (left) and mean basin precipitation (right) for drainage areas of 1, 10, and 100 km² along glaciated valleys (black squares), partially glaciated valleys (triangles), and unglaciated fluvial valleys (circles). Mean basin slope derived from U.S. Geological Survey 10 m digital elevation models; mean basin precipitation based on 4 km grid of mean annual precipitation from 1961–1990 (Daly et al., 1994).

DISCUSSION AND CONCLUSIONS

Systematic increases in valley size with increasing drainage area (and therefore ice flux) for basins occupied by alpine glaciers parallel prior reports that fjord cross sections scale with drainage area and therefore ice flux (Roberts and Rood, 1984; Augustinus, 1992a). The relatively small differences in mean basin slope and precipitation between the three valley types for large basins (i.e., 100 km²) indicate that morphometric differences noted here primarily reflect differences in the processes of valley development. On the west slope of the Olympic Mountains, valleys with extensive glaciation are larger than those that underwent minor glaciation, which are in turn larger than unglaciated valleys. Compared to rivers, alpine glaciers removed two to four times greater rock mass in carving their valleys in the same geologic and climatic setting. This greater removal of rock through glacial widening and deepening provides an estimate of erosion associated with conversion of fluvial valleys to glacial-valley form. However, changes in valley shape or dimensions do not address directly rates of erosion, because a change in valley shape may trigger only a transient increase in erosion rates during the period of adjustment from one equilibrium form to another.

Differences in the size of fluvial and glacial valleys are not uniformly distributed along the valley system, and there is little difference in the morphometry of headwater valleys. The progressively larger downvalley differences imply that a nonlinear glacial erosion law describes valley excavation in glaciated terrain and leads to formation of hanging valleys in valley systems by overexcavating large valleys, as predicted by a physically based model of glacial-valley longitudinal-profile evolution (MacGregor et al., 2000). In the eastern Sierra Nevada, Brocklehurst and Whipple (2002) also found that glaciers increased relief by <100 m in basins with drainage areas of 3–36 km² and lengths of 3.4–16.4 km. The lack of relief enhancement in glacial source areas in both the Olympics and the Sierra Nevada suggests that significant relief enhancement is limited to large alpine glaciers.

Previous analyses of the Olympic Mountains concluded that threshold slopes were developed throughout the core of the range; mean slopes are relatively uniform, even though there are large gradients in rock-uplift rate across the range (Montgomery, 2001). The greater relief observed in glacial valleys could be reconciled with development of threshold slopes by the greater width of glaciated valleys. Close examination of the DEM of the study area suggests that the glaciated valleys of the Hoh and Queets Rivers expanded at the expense of tributary valleys. In particular, the drainage pattern suggests that what appears to have once been the headwaters of the Solleks River has been captured by widening of the Queets River valley.

An intriguing implication of the greater excavation of rock to form larger valleys during the Pleistocene is the potential influence on elevations in the core of the range. The substantial widening and deepening of valleys in response to glaciation implies the potential for isostatic rebound to raise surrounding peaks and suggests that some of the elevation of the highest peak in the range (Mount Olympus) may reflect Pleistocene valley widening in the surrounding moat of large valleys. Montgomery and Greenberg (2000) calculated that excavation of valleys in the core of the range could have resulted in as much as 500–750 m of isostatically induced rock uplift at Mount Olympus. If glaciers more than doubled the preglacial valley volume in the core of the range, as implied by this analysis, then onset of Pleistocene glaciation could have raised Mount Olympus by several hundred meters. Offset of maximum glaciogenic relief well downstream of glacier source areas is consistent with the potential for positive feedback in which widening and deepening of large glaciated valleys enhance rock uplift in glacier source areas, leading to higher elevations, greater snow accumulation, and larger glaciers (Brozovic et al., 1997).

The generally greater width of glaciated valleys in the Olympic Mountains demonstrates the importance of valley widening as part of geomorphic response to climate change. The effects of glacial erosion on the net excavation of rock from the valley system of the western Olympics demonstrate the potential for glaciation to increase valley size and relief in alpine topography. Although rates of erosion may be greatest under an oscillating dominance of glacial and fluvial processes (Church and Ryder, 1972), an implication of the findings reported here is that the onset of Pleistocene glaciation should have resulted in a pulse of sediment yield in areas subject to alpine glaciation during the period while valleys adjusted to new forms.

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