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Denudation of Small Alpine Basins, Nanga Parbat Himalaya, Pakistan

*John F. Shroder, Jr.,**
Rebecca A. Scheppy,†
*and Michael P. Bishop**

*Department of Geography and Geology, University of Nebraska at Omaha, Omaha, Nebraska 68182, U.S.A.
shroder@cwis.unomaha.edu

†Department of Geology, University of Kansas, Lawrence, Kansas 66045, U.S.A.

Abstract

Thirty-three debris fans and five small alpine basins on the south side of the rapidly uplifting Nanga Parbat Himalaya of northern Pakistan were assessed to determine how much alpine processes contribute to the overall denudation of the massif. A high-resolution digital elevation model was used to measure the volume of the small alpine fans and a few basins in the Rupal valley. These volumetric estimates, coupled with time-constraining dates from cosmogenic-nuclides of glacially exposed rocks and infrared-stimulated luminescence of sediments, indicate that estimated average denudation rates in these systems have been ~2 mm yr^{-1} over the past 4600 to 6000 yr since the last major deglaciation. This is similar to other estimates of rates of denudation in the Himalaya.

Introduction

BACKGROUND

The Nanga Parbat massif, at 8125 m altitude (Fig. 1), is the ninth highest mountain in the world, and an area of rapid erosional unroofing (Zeitler, 1985; Shroder, 1989, 1993; Burbank et al., 1996). The Nanga Parbat Project, from which this paper is a product, is a multidisciplinary investigation of the tectonics and topography of the massif. Members of the project are assessing very young, high-grade metamorphism, partial melting, high fold and fault strain (Zeitler et al., 1993), and the rapid denudation by mass movement, glaciers, rivers, and catastrophic breakout floods (Bishop et al., 1998a, 1998b, 1999; Shroder, 1998; Shroder et al., 1998). Analysis of the topography and denudation of the massif is critical to understanding the petrologic and tectonic evidence of denudation, which has been sufficiently rapid to induce significant pressure and temperature changes at depth.

Following the continental collision of India with Asia ~50 Ma ago, the Indian plate continued to move north to force up the Himalaya chain from Afghanistan to Burma. Nanga Parbat is an up-faulted, pop-up or flower structure engirdled with inward-dipping reverse faults (Seeber and Pêcher, 1999) that stands near the western end of the High Himalaya chain and has an anomalous north-northeast trend between its main bounding faults of similar direction. The felsic basement gneisses of Nanga Parbat represent the northernmost expression of the Indian plate that has thrust up and through the previously overlying mafic rocks of the Kohistan-Ladakh island arc caught between the colliding plates (Zeitler, 1985).

Zeitler et al. (1989) and Winslow et al. (1994) estimated an uplift or exhumation rate of the Nanga Parbat area of 4 to 8 mm yr^{-1}, on the basis of geochronologic evidence that the massif had been exhumed 10 km in the past 10 Ma, 6 km of that in the past 1.3 Ma of the Quaternary. Burbank et al. (1996) used cosmogenic-radionuclide exposure ages to estimate bedrock incision rates by the antecedent Indus River of 2 to 12 mm yr^{-1} across the Nanga Parbat uplift. We have made 15 preliminary measurements of glacier and river incision rates below cosmogenically dated or correlated glacier erosion and deposition terraces on the massif. These maximum incision rates of bedrock at specific locations are highly variable, but average ~2.2 ± 1.1 cm yr^{-1} and can be as high as 5.2 cm yr^{-1} close to the zones of most active faulting and deepest river incision. In addition, localized rates of denudation at Nanga Parbat for several large glacier and river basins range from 0.7 to 2.5 cm yr^{-1}. Catastrophic floods, resulting from the breaking of repetative landslide dams, can result in rates of denudation as high as 12 cm yr^{-1}. Such rapid and localized, but still short-term and episodic, denudation at Nanga Parbat appears responsible for the extreme relief at a multitude of scales (Shroder et al., 1998; Shroder and Bishop, in press).

Denudation processes on Nanga Parbat are controlled in part by strong climatic gradients (Hewitt, 1993). Because of its great height and bulk, the Nanga Parbat massif serves as a climatic divide between the continental air masses of cold and arid central Asia and the maritime air masses of the Arabian Sea, leaving in rainshadow various regions of the massif. This varies locally depending upon aspect and relief, but in general, the northern regions of the massif are more arid than the southern (Scott, 1992). Year-round, orographic precipitation provides snowfall on the peaks in excess of 2000 mm yr^{-1}, whereas valley floors at lower altitudes can receive as little as 200 mm yr^{-1} of precipitation, with temperatures up to 50°C in summer months (Gardner, 1986). Debris fans, however, can be covered with thick avalanche snows for much of the summer season. For example, in 1996 following a winter of heavy snows, five fans with a northern aspect in the mid-Rupal valley between Bhazin and Chungpar glaciers (Fig. 1) were completely snow-covered in late July. At the same time in the Chungpar valley, fans with an eastern aspect still had substantial snow from avalanches.

PURPOSE

The geomorphic processes responsible for the denudation of the alpine valleys on Nanga Parbat can be subdivided into two large groups—glacial and nonglacial. Glacial processes appear to be highly effective in removing large amounts of sediment from the Nanga Parbat massif (Gardner and Jones, 1993). Large areas (302 km^2) of the mountain are presently glacierized (Kick, 1980, 1994), and much more was covered with ice during the Pleistocene (Shroder et al., 1989; Scott, 1992; Khule, 1996). Nonglacial processes affecting formation of alpine basins and fans at Nanga Parbat include mass movement, fluvial processes, and catastrophic flood-flushing (also influenced by glaciation).

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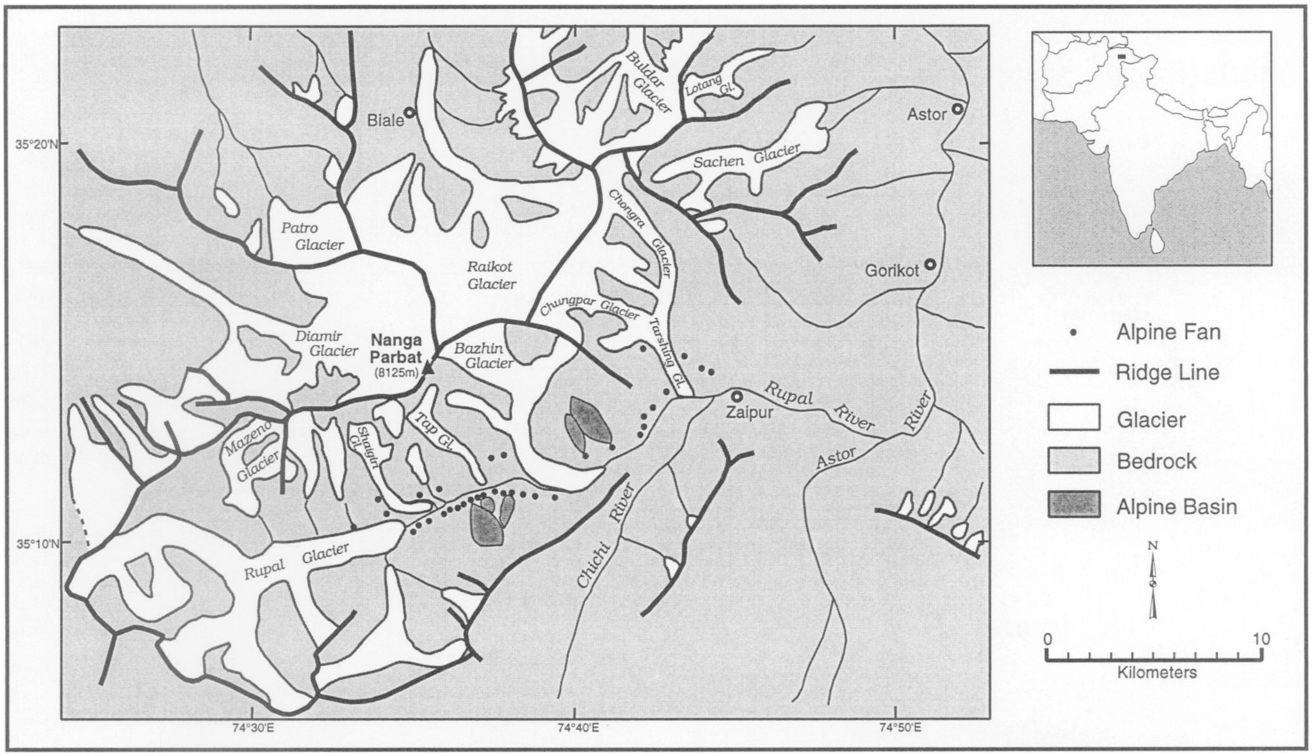

FIGURE 1. Location of Naga Parbat study area and map of the Rupal Valley on the south side of the massif wherein 33 of 74 alpine basis and fans were analyzed.

An earlier pilot project to assess denudation in two small basins above Biale in the Raikot valley on the north side of Nanga Parbat was unsuccessful. A variety of data sets was used to estimate rates of denudation, resulting in irreconcilably disparate rates. This was attributed to use of the somewhat inaccurate, old (1937) topographic map, the difficulty of accurate measure of basin and fan volumes, the erosion of much fan sediment by periodic debris flows dated with tree rings (Shroder et al., 1996), and the experimental nature of the ^{3}He cosmogenic isotope signal used to model denudation (Phillips et al., 1996; Phillips, 1997).

The purpose of the study described here was to use more advanced techniques to characterize and measure the volume of some of the smaller alpine basins and their polygenetic debris fans in the Rupal valley of Nanga Parbat in order to calculate reasonable estimates of rates of denudation (Scheppy, 1997).

Geomorphology of Small Alpine Basins and Fans on Nanga Parbat

The characteristic glaciated, U-shaped valley walls of Nanga Parbat are commonly dissected by alpine erosional basins with polygenetic depositional fans at their mouths (Figs. 1, 2). The fans are one of the most common depositional forms in the valleys, and are rarely far enough apart to be completely separate. Fans range in scale from isolated small slope failures to extensive areas of polygenetic processes and complex slope movements. Polygeneity of the fans is demonstrated by their varying slope gradients, many of which are low-angle, fluvial or debris-flow dominated alluvial fans, whereas others have a high angle of repose with little vegetative cover characteristic of rockfall deposition. Seven main processes of formation of alpine basins and fans were observed or inferred: (1) debris flows; (2) talus and rockfalls; (3) wet-snow avalanches; (4) dry-snow avalanches; (5) nonglacial fluvial action; (6) glacial meltwater outwash; and (7) polygenetic, ice-marginal ramp action (Kuhle, 1990).

The major factors controlling these alpine slope processes are tectonics and climate. The extreme relief produced by the active coupling of denudation with tectonics (7 km in 21 km, north side; 4.6 km in 6 km, south side) at Nanga Parbat leads to increased steepening of the climatic-geomorphic zones and a tendency for distribution of process according to an altitudinal gradient (Hewitt, 1993). Most of the polygenetic basins in this study extend into Hewitt's zone II (humid, high alpine tundra) and sometimes into zone I (humid, perennial ice), but the fans fall within zones III (subalpine montane) and IV (semiarid, submontane). Mass-movement processes dominate most basins and fans, although the processes of formation are more commonly transitional than distinct.

Debris flows are one of the most common mass-movement mechanisms in the Himalaya (Goudie et al., 1984; Shroder, 1993), because of abundant loose source material that can be mobilized by torrential rain or rapidly melting snow. Such debris at Nanga Parbat is provided by the extreme relief and associated high freeze and thaw on the higher slopes. Typical debris flows on Nanga Parbat have exhibited one or more waves of wet debris through a channel and over the banks to leave levees of coarse clasts on channel sides. On the bigger fans at Nanga Parbat, large sieve lobes of rubble from debris-flow emplacement occur in many places.

Rockfall appears common to every fan in the study. It is due to the high relief and highly fractured crystalline rock of the massif. The rocks of the mountain are resistant crystallines but their actual strength is controlled largely by the size and orientation of jointing and foliation with respect to the hillslope angle (Selby, 1993). The active extreme tectonism and high seismicity of the region, coupled with the heavy overburden of past and

FIGURE 2. Photograph taken in 1996 between Tap and Bazhin glaciers at 4500 m looking west-southwest at the upper Rupal Valley on the flank of Nanga Parbat. A variety of polygenetic alpine basins and fans (labeled) show in this view, with steeper, bare, rubble-covered fans on the left (south) and more gentle, vegetated fans on the right (north) side. The debris-covered Tap Glacier and terminal lake occur in the foreground, with Shaigiri and Rupal glaciers in the background. Comparison to older (1934) photographs by Finsterwalder et al. (1935) shows that meltwater channels on fan 6NTS have switched from a western to an eastern location in the intervening 61 yr.

present glacial ice has left the bedrock macroscopically and microscopically fatigued, and highly susceptible to fracture and denudation (Scott, 1992). Pervasive frost shattering, vigorous erosive unloading, and probable chemical weathering of the rock also reduce rock shear strength (Goudie et al., 1984; Whalley et al., 1984).

Snow avalanches in the western Himalaya are large, pervasive, and transport plentiful coarse, fine, and vegetative debris (de Scally and Gardner, 1994, 1987; Bell et al., 1990). On Nanga Parbat we have observed chaotic fan fabrics and impact pits (Luckman, 1977; Corner, 1980) from wet-snow avalanches, but we also noted ordered fabrics of slabby clasts oriented with the slope as the snow melted. Dry-snow avalanches involving the total snow depth probably have caused erosion of debris from basin walls and the basal debris in the avalanches may have further abraded avalanche tracks (Bell et al., 1990).

Alluvial fans in the western Himalaya tend to have low gradients of 2 to 7°, and are usually dominated by a powerful meltwater stream (Goudie et al., 1984). A few such fans occur on Nanga Parbat (Fig. 2), but are not common in the narrow valleys. Fans of glacial outwash occur at the termini of several hanging glaciers in the Rupal valley. Debris is transported down slope by falling or by the glacier meltwater stream.

Ice marginal ramps were described by Kuhle (1990) as depositional landforms that develop on the outer slopes of lateral moraines in semiarid regions. They are several kilometers long at Shaigiri and Tarshing Glaciers in the Rupal Valley (Fig. 1) and their source area is the till of the lateral moraines. Water is supplied to the process by meltwater seepage from the glaciers, as well as by precipitation. Debris rolls and slides down the steep slopes of the lateral moraine and the fan takes on a strong concave profile without the common peripheral fan shape in plan.

Chronology

The Holocene chronology of deglaciation at Nanga Parbat and the initiation of development of debris fans from the newly exposed valley walls is critical to calculating rates of denudation throughout the massif. Cosmogenic nuclides (^{3}He, Phillips 1997; ^{10}Be, Phillips, e-mail comm., 1998) were used to date exposure of rocks and infra-red stimulated luminscence (ISRL; Rendell, e-mail comm., 1997) to date deposition of lake beds in the Rupal and Astor valleys for this study. Remnants of high lateral moraines exist throughout the valleys of Nanga Parbat and seem to represent a wide range of ages: (1) ice advance in late Pleistocene time at ~55,000 yr BP (Phillips et al., 1996), prior to the last glacial maximum; (2) an advance of the last glacial maximum in the latest Pleistocene; (3) or an advance in early to middle Holocene. The high lateral moraine in Rupal valley exist at about 3800 m and are probably the temporal equivalent in the Astor valley of the monsoon-enhanced ice advance in early Holocene that was downwasting at 6640 ± 800 ISRL yr BP, or in the Raikot valley of the Fairy Meadows moraine dated at 5300 ± 500 ^{10}Be yr BP (Phillips, e-mail comm., 1998). We make the assumption that when the ice last retreated from the Rupal Valley the exposed slopes were subject to erosion to produce small alpine basins and fans. Using this reasoning, and given general uncertainties in dating and in rates of glacial wasting to expose the Rupal Valley to the point where the fans could begin to accumulate, we assume that the debris fans we measured in the Rupal valley began ~6000 yr ago. This may be slightly too old, because Phillip's (e-mail comm., 1998) ^{10}Be dates indicate that the Rupal valley was largely deglaciated only by ~4600 BP. Accordingly we used both figures of 6000 and 4600 BP in our calculations in order to obtain a reasonable range of rates.

Methods

Thirty-three of the 74 alpine basins and fans in the Rupal valley on the south side of Nanga Parbat were field mapped and delineated on a topographic map (1:50,000 scale). Current depositional processes on the fans were identified, based upon present-day morphological and sedimentological expression. Other morphological and depositional information were also collected, including fan shape and gradient, clast lithology and texture, and vegetation type and coverage (Scheppy, 1997). Data acquistion consisted of obtaining reference information using a global positioning system (GPS), ground photography, morphometric de-

TABLE 1

Volumes derived from the DEM of small alpine fans and their source basins in the Rupal Valley of Nanga Parbat, together with denudation rates derived for both the 6000 yr and the 4600 yr time spans since deglaciation.

Fan Number	Fan Volume V_f (m³)	Basin Area A_b (m²)	Solid Rock Volume V_r (m³)	Rock Thickness L_r (m)	Denudation Rate D_f (6000 yr) (mm yr⁻¹)	Denudation Rate D_f (4600 yr) (mm yr⁻¹)
6NTS	81,247,850	3,719,600	60,935,888	16.38	2.7	3.6
7NTS	4,353,117	402,000	3,264,838	8.12	1.4	1.8
2NSR	3,819,929	652,800	2,864,947	4.39	0.7	1
3NSR	17,807,548	5,214,600	13,355,661	2.56	0.4	0.6
4NSR	39,833,518	7,478,800	29,875,138	0.4	0.1	0.1
1STS[a]	65,034	30,600	48,776	1.6	0.3	0.3
2STS[a]	24,112,305	1,876,800	18,084,228	9.6	1.6	2.1
3STS	1,000,000	96,400	750,000	7.78	1.3	1.7
4STS	321,927	80,000	241,445	3.02	0.5	0.7
5STS	371,782	256,400	278,837	1.05	0.2	0.2
6STS	1,701,382	138,800	1,276,037	9.19	1.5	2
7STS	553,601	222,000	415,201	1.87	0.3	0.4
1SSR	14,524,815	6,683,000	10,893,611	1.63	0.3	0.4
2SSR	340,949	84,600	255,712	3.02	0.5	0.7
3SSR	1,585,586	1,076,400	1,189,190	1.1	0.2	0.2
1NBT	3,250,506	365,600	2,437,880	6.67	1.1	1.5
2NBT	1,548,266	104,800	1,161,200	11.08	1.9	2.4
2SBT	6,616,140	1,139,200	4,962,105	4.36	0.7	0.9
4SBT	124,340,012	3,392,000	93,355,009	27.52	4.6	6
5SBT	4,223,217	1,143,200	3,167,413	2.77	0.5	0.6
7SBT[a]	711,425	400,800	533,569	1.33	0.2	0.3
1WCV	13,036,609	1,031,200	9,777,457	9.48	1.6	2.1
2NCB	2,951,667	2,208,000	2,213,750	1	0.2	0.2
3NCB	526,739	674,800	395,054	0.59	0.1	0.1
5NCB	705,958	608,800	529,469	0.87	0.1	0.2
6NCB	30,337,493	5,927,600	22,753,119	3.84	0.6	0.8
7NCB	1,357,250	166,800	1,017,938	6.1	1	1.3
9NCB[a]	41,921,351	1,618,000	31,441,013	19.4	3.2	4.2
10NCB[a]	48,445,677	862,800	36,334,257	42.11	7	9.2
2SCB	852,780	35,200	639,585	18.17	3	4
1NCAV	64,547,402	2,350,800	48,410,551	20.59	3.4	4.5
3NCAV	547,400	566,000	410,550	0.73	0.1	0.2
5NCAV	383,437	393,200	287,578	0.73	0.1	0.2
Mean Denudation Rate $\bar{D}_f \pm \sigma$					1.3 ± 1.5	1.7 ± 2

[a] Fans of basins listed in Table 2.

scriptions, and field maps. A panchromatic stereo-pair from the SPOT satellite was obtained in October 1996 and a digital elevation model (DEM) was generated with a resolution of 20 m and a vertical accuracy of ±8–12 m. The reference data were used to characterize the fans. The point data and the DEM were put into a geographic information system (GIS) to facilitate spatial analysis of basins and fans.

The alpine basins and fans were delineated, digitized, and extracted as a subset from the DEM. Points along basin ridges were identified and used to create an imaginary surface over each basin using an interpolation algorithm (kriging). This procedure was used to create a low frequency first-order approximation of the "prebasin surface" so that basin volume estimates could be used to estimate rates of denudation. This assumption seemed reasonable for the five smaller basins incised into glacially smoothed rock sidewalls, but not for the larger basins that would have existed before the readvance of the early to middle Holocene. In this way we compared rates of denudation produced from different methods.

FAN VOLUMES

Thirty-three of the 74 fans associated with the alpine basins in the Rupal valley (Table 1) were analyzed with the assumption that the Rupal glacier scoured the valley bottom during its advance, taking with it any prior fan sediments. The fan sediments are, therefore, postglacial. These 33 fans and source basins are those that could be delineated on the DEM.

Fan perimeters were digitized and measured to obtain surface areas (A_f). The base altitude of the fan was subtracted from the apex altitude to give height (h). Because alpine fans tend to be cone segments, volume was calculated using the equation, $V_f = A_f{*}h/3$. For fans with a concave-up profile, volumes are maxima. For fans with a rectilinear profile, the volume estimate is most accurate. Nevertheless, this method assumes that the fan base is situated on a reasonably flat valley floor, which probably produced some overestimation of volumes. We believe this overestimation may be somewhat compensated by other factors, as explained below.

In general, rock weathering in the western Himalaya produces blocky clasts ranging in size from a few centimeters to many meters, and fines that are dominantly sand- and silt-sized (Derbyshire et al., 1984; Scott, 1992). Nonglacial debris falling from the walls of glacier basins onto the ice of Nanga Parbat represents 11 to 39% silt, with sand being nearly as high. Hewitt (1988) documented up to 35% fines from rock weathering in the

Karakoram. While these numbers are highly variable, they do indicate that plentiful fine-grained sediment is produced here as a large portion of nonglacial processes. Such sediment is, therefore, a large component of the alpine fans that can be considered in calculation of fan volumes and porosities, as well as in the subsequent loss of fines through diverse processes.

Potential errors in calculating volumes of fan sediments, in comparison to their generally larger basins of origination, include sediment transport across and away from fans, removal of fine sediment from fans by eluviation, and obscuring of fan size by valley-fill cover. No allowance was made for losses of sediment by transport away from the fans as no collateral information exists to permit such estimates. Nevertheless we are aware that numerous catastrophic flood-flushing events in the Rupal valley have removed plentiful sediment in the past (Shroder et al., 1998). The exact percentage of eluviation loss is also unknown. In addition, the thickness of valley sediment obscuring fan perimeters in the Karakoram commonly exceeds 700 m (Owen and Derbyshire, 1988). In the actively eroding area of Nanga Parbat, the fill in Rupal valley is not likely to be as thick, but it does cover a portion of the fan-base sediments. Taken together, these factors indicate that our fan size estimates should represent underestimations or minimum values of material actually denuded from the basins. Therefore our estimates of rates of denudation based upon the slightly overestimated fan volumes with a porosity of 25% are believed to be compensatory and, therefore, reasonable.

Denudation rates based upon the fan volumes (D_f) were produced using the following equation:

$$D_f = L_r/t \tag{1}$$

where L_r is the total rock thickness eroded from a basin, and t represents time. The total rock thickness is estimated as:

$$L_r = V_r/A_b$$

where V_r is solid rock volume, and A_b is basin area.

Solid rock volume $Vr = V_f\, n_f$, where V_f represents the fan volume and n_f is an estimated total fan porosity of 25% (0.75), based on the fact that smaller grains (silt and sand) are estimated to have porosities ranging from 20 to 50%, and gravel from 25 to 40% (Selby, 1993).

BASIN VOLUMES

Only five small basins in the Rupal valley were evaluated using basin volumetric analyses in order to compare rates of denudation using this method to the "fan volume" method (Table 2). The small sample size was dictated by the selected small basins most likely to have had no preglacial development and by the need for moraines to occur above each basin. Only the portion of the basin below the moraine was used to calculate basin volume. Similarly, the basin needed to be large enough for acceptable spatial-interpolation results, which further reduced sample size. Even taking all these factors into consideration, the basin volumes were still larger than the fan volumes, although the precautions taken to eliminate the disparities should have decreased overall variance to a minimum.

Denudation rates for basins (D_b) were calculated according to:

$$D_b = V_b/A_b/t \tag{2}$$

where V_b = bedrock volume eroded from area A_b of a basin over time (t).

TABLE 2

Estimations of denudation rates based upon volume of five small basins compared to the rates calculated for the associated fan volumes (Table 1) in the Rupal Valley of Nanga Parbat, for the 6000 yr and 4600 yr time spans since deglaciation.

Alpine Basin and Fan Number	Denudation Rate (mm yr^{-1})[a]			
	D_b6000 yr	D_b4600 yr	D_f6000 yr	D_f4600 yr
1STS	2.6	3.4	0.3	0.3
2STS	5.2	6.8	1.6	2.1
7SBT	4.4	5.8	0.2	0.3
9NCB	8.6	11.2	3.2	4.2
10NCB	5.9	7.7	7.0	9.2
$\bar{D}_b \pm \sigma$	5.4 ± 2.2	7 ± 2.9	2.5 ± 2.8	3.2 ± 3.7

[a] D_b-denudation rates for basins; D_f-denudation rates for fans.

Results

DENUDATION RATES

Rates of denudation were calculated using the methods of fan volume (D_f) (Table 1) and basin volume (D_b) (Table 2). In general, the volume of fans in the Rupal valley can be seen to be smaller than the basins from which they come. The disparity between fan volume and basin volume indicates that: (1) most basins have some prior history of erosion; (2) some sediment eroded from the basins bypassed the fans; and (3) some sediment was re-eroded from the fans.

For the time period of 6000 yr selected since the deglaciation of the Rupal Valley, the average rate of denudation and variance ($D_f \pm \sigma$) is estimated to be 1.3 ± 1.5 mm yr^{-1} (Table 1). If the figure of 4600 yr since deglaciation is used, then the average denudation rate and variance is estimated to be 1.7 ± 2 mm yr^{-1}. Furthermore, the large variation ranging from 0.1 to 9.2 mm yr^{-1} presumably reflects a variety of process rates responsible for differential denudation. In comparison, the average rate and variance from the basin volumetric analyses is 5.4 ± 2.2 mm yr^{-1} for the period of 6000 yr and 7 ± 2.9 mm yr^{-1} for the period of 4600 yr (Table 2). This larger estimated denudation rate may be partly a reflection of some erosion prior to the last glaciation, as well as a consequence of the methodology.

The overall average denudation rates for the alpine basins in the Rupal valley of Nanga Parbat, derived from averaging all D_f values for both time estimates, is ~2 mm yr^{-1}, based upon the conservative D_f estimates and the variance. This is about an order of magnitude less than the rates of incision and denudation measured in the main valleys in the Nanga Parbat region (Shroder and Bishop, in press).

In comparison to data from other areas, however, the rate might still seem high. For example, Bovis and Thorn (1981) made order of magnitude estimates for soil-loss variation on a Colorado interfluve that showed a mean surface lowering rate of only 0.1 mm yr^{-1}. Young (1969) reviewed world-wide data and calculated that areas of steep relief were lowered at mean rates of 0.5 mm yr^{-1}. Caine (1974) noted that rates of cliff retreat in alpine areas vary from practically nothing to ~1 mm yr^{-1}. In the Kumaun Himalaya of India, however, Valdiya and Bartarya (1989) calculated a denudation rate of 1.7 mm yr^{-1} from mass movement. At the higher end of erosion rates, Small (1987) noted supraglacial rockwall retreat of 2.16 mm yr^{-1} in the Swiss Alps. Watanabe et al. (1998) used ^{14}C dating of small alpine debris cones in the Langtang Himal to measure rates of denudation that ranged from 3.2–6.8 mm yr^{-1}, with a mean of 4.5 mm yr^{-1}. Brunsden et al. (1981) noted the effects of monsoonal precipitation on slopes and channels in eastern Nepal that produced rates of denudation of ~5 mm yr^{-1}. Thus the average rate of differential denudation of ~2 mm yr^{-1} that we have established for the small alpine basins in the upper Rupal Valley, far from the deeply incised valleys where rates are greater, appears to be reasonable.

Conclusion

A first-order approximation of differential denudation of small alpine basins on the south side of Nanga Parbat was accomplished to compare them with known higher rates produced by glaciers, fluvial processes, catastrophic flooding, and low frequency, high-magnitude mass-movement events elsewhere on the massif. An average rate of ~2 mm yr^{-1} for the denudation of small alpine basins in the Rupal valley is considered a minimum estimate for such an active area. Sediment transported across or eroded from the alpine fans by elutriation, deflation, and known catastrophic-flood flushing throughout the Rupal Valley (Shroder et al., 1998) has not been included in these calculations. Loss of mass from the fans by whatever means, coupled with a possible deglacial history that was underway <6000 yr ago would, of course, increase these first-order estimates.

The Nanga Parbat massif owes its origin to erosionally induced failure of the crust near the deep gorge cut by the Indus River as it exits the Himalaya and enters the foreland basins (Shroder and Bishop, in press). Spatially and temporally differential denudation is thought to be responsible for the high topographic variability and extreme relief of the Nanga Parbat Himalaya. Denudation of the small alpine basins on the massif is rapid but an order of magnitude less than the rates of maximum incision and denudation in the large valleys on the flanks of the massif.

Acknowledgments

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