Rapid, long-term rates of denudation

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ABSTRACT

High rates of erosion (1–15 mm/yr) of fluvial strata have persisted over intervals of 0.2–1.5 *m.y. and across areas of 60–2000 km^2 in the Cenozoic foreland basin of northern* Pakistan. These rates occur in areas associated with thrust shortening, and they indicate that erosion nearly kept pace with the rates of latest Miocene to Pleistocene uplift. Such high rates of erosion are predicted to promote hindward imbrication of thrusts and to reduce the amount of subsidence directly attributable to thrust loading.

INTRODUCTION

Any attempt to understand or model the evolution of terrestrial landscapes must deal with episodes of uplift and erosion. Despite their importance, however, a good understanding of the rates and variability of these processes has yet to be achieved (England and Molnar, 1990). In the absence of such knowledge, geologists cannot reliably reconstruct dynamic landscapes, nor can modelers accurately predict the duration and impact of processes, such as the emplacement and erosion of thrust loads. Although numerous rates of chemical and mechanical denudation have been calculated for short (0–10 ka) intervals (e.g., Scott and Williams, 1978; Colman and Dethier, 1986), we don't know the optimal way to extrapolate these diverse rates to long-term processes. It is clear, however, that rates of erosion are often highly correlated with rock type, such that a thrust that uplifts a thick sequence of readily eroded strata will generate a significantly different topography and impose a fundamentally different load than will a thrust that uplifts a similar thickness of highly resistant rocks in the same climatic regime. Although some lithologically dependent rates of denudation have been investigated previously (Creasey et al., 1986), well-calibrated, long-term rate calculations are uncommon. Here we present several examples of sustained high rates of erosion in the Himalayan foreland basin of northern Pakistan and briefly discuss the implications of these rates for landscape evolution and structural styles.

METHODOLOGY

The calculation of reliable long-term rates of denudation is typically hampered by several obstacles: it is often difficult to establish accurately the volume of rock that was denuded from a particular area, and tight age constraints cannot commonly be placed on the beginning and end of a denudational episode. Owing to the youthfulness of the Himalayan landscape and because some denudational events have not been overprinted by subsequent deformation, however, it is often possible to reconstruct the volume of eroded rock with considerable confidence. Because predeformational stratal geometries can be reliably reconstructed (Pennock et al., 1989), the preservation of formerly contiguous strata serves as a reliable guide to eroded thicknesses. Chronologies of uplift and denudational events in northern Pakistan have been attained through magnetostratigraphic studies and related fission-track dating (Johnson et al., 1982; Raynolds and Johnson, 1985). Some of the denudational events described below are continuing today. For these, only the time of initiation needs to be known, whereas for others, both the timing of initiation and the duration must be determined. The rates cited here are calculated by dividing the average thickness of sediment eroded from a region by the duration of the erosional episode. Consequently, these calculations represent average, long-term rates of erosional stripping.

There are several sources of potential errors in the calculated rates. First, because the events of interest usually do not coincide with magnetic chron boundaries, it is necessary to estimate stratal ages based on extrapolations or interpolations of accumulation rates determined for the underlying or overlying strata. Because accumulation rates tend to decelerate during the Pliocene-Pleistocene (Raynolds and Johnson, 1985), we would expect age estimates based on extrapolations into younger strata to be older than the actual stratal age. Second, the time span determined from bracketing dates for an episode of erosion is almost always longer than the episode itself, because bracketing dates only refer to the youngest and oldest *preserved* strata that predate and postdate the event, respectively. The amount of erosion of underlying strata and/or nondeposition of overlying strata determines how well constrained the event can be. Third, it is usually impossible to specify how rates of processes may have changed during the episodes of interest. Although 90% of the erosion may have been accomplished in 10% of the time, in the absence of dates during the event, only mean rates can be cited. Fourth, the beginning and/or end of some events must be inferred from the stratal record. For example, a large-

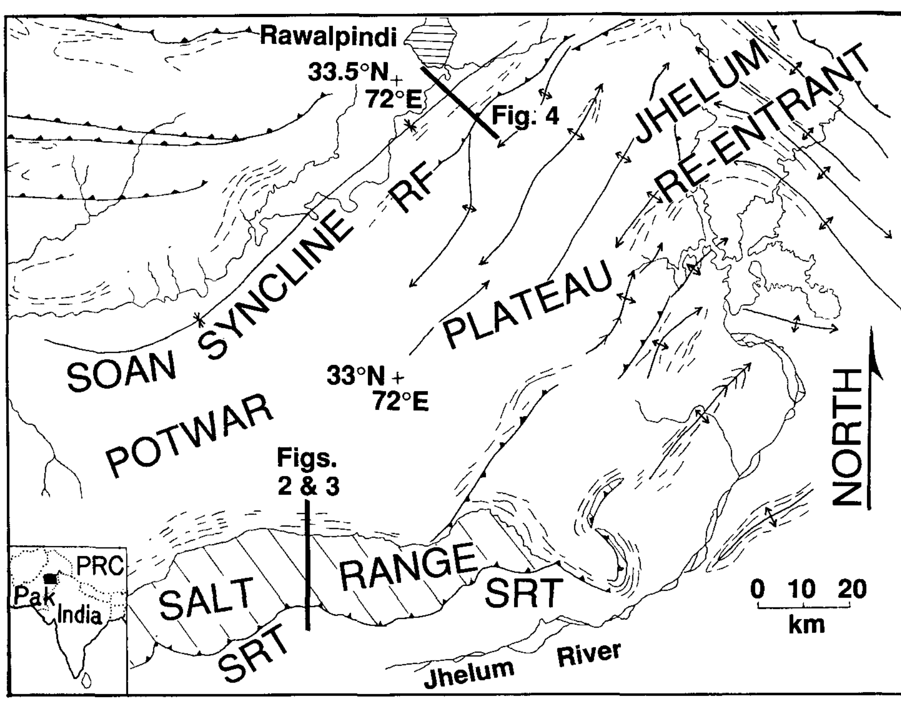

Figure 1. Location map of Himalayan foreland in northern Pakistan showing studied areas of Salt Range (Figs. 2 and 3) and Soan syncline (see Fig. 4) along southern and northern margins of Potwar Plateau. RF = Riwat fault; SRT = Salt Range thrust. In inset map, Pak = Pakistan, PRC = People's Republic of China.

scale drainage reorganization may be logically attributed to the initiation of nearby uplift, but other potential causes, such as changes in hydrology, cannot always be excluded. It is also possible that uplift and erosion may have commenced prior to the time of initiation that is shown by preserved strata. This would lead to an overestimation of rates. Fifth, most volumetric calculations are based on the predictable nature of thickness changes across broad regions of the foreland of northern Pakistan (Johnson et al., 1982; Raynolds and Johnson, 1985). If significant undetected discontinuities occurred within the volumes of the eroded rock, volumetric estimates would be incorrect. Sixth, neither hanging-wall cutoffs nor all fold limbs are consistently preserved. Consequently, unaccounted-for volumes of rock may have been removed. Because of these multiple sources of potential errors, the rates calculated below are given as ranges, and generally they represent minimum estimates.

RATES OF UPLIFT AND DENUDATION

Salt Range

The Salt Range delineates the southern margin of a >100-km-wide, salt-lubricated detachment underlying the Potwar Plateau in northern Pakistan (Fig. 1). The hanging wall consists of a Phanerozoic sequence comprising Eocene to Paleozoic carbonate and clastic strata (Gee, 1980) that are up to 1 km thick and are overlain by fluvial strata that form a southward-tapering wedge from 6 to 3 km thick (Fig. 2). Two intervals of thrusting, uplift, and denudation can be defined in parts of the range. The initial stage of emplacement of the Potwar allochthon transformed the Potwar Plateau into a piggyback basin and transported Paleozoic strata at the base of the allochthon up the footwall ramp to the latest Miocene erosional surface (Burbank and Beck, 1989), from whence Paleozoic clasts were shed northward into the piggyback basin. Given a ramp inclined at 30°–45° (Baker et al., 1988), ~4–5 km of shortening and 2.5–3 km of stratal uplift were required to achieve this geometry (Fig. 2). The amount of erosion must nearly have balanced the amount of uplift, because the entire thickness of fluvial molasse strata (2.5–3 km) had to be removed along the top of the thrust sheet in order to expose the underlying Paleozoic strata to erosion. Because information is unavailable regarding the topography of valleys incising the uplifting hanging wall, the volume of eroded strata can only be estimated.

The duration of this initial thrusting and erosion event can be inferred from the coeval sedimentary record. A major transformation of the depositional system in the southern Potwar Plateau occurred 5.9–5.8 Ma (Mulder and Burbank, 1991), when, in apparent response to uplift of the southern edge of the Potwar allochthon, smaller, northeast-directed fluvial systems began to replace the southeast-flowing paleo–Indus River. At 5.5–5.4 Ma, Paleozoic clasts derived from the thrust tip first appeared in the piggyback basin (Burbank and Beck, 1989). Thus, over an interval of ~0.3–0.5 m.y., 2.5–3.0 km of fluvial strata were eroded at rates of 5–10 mm/yr. This should represent a limiting rate at the area of maximum incision, whereas, given typical hillslope profiles, the mean erosion rate across affected regions of the thrust tip should be 60%–90% of this amount. Although the size of the affected area is highly speculative, if mean valley slopes of 10° are postulated, then an area of >300 km^2 would have been eroded adjacent to a single river. Gentler slopes would result in greater volumes of eroded material.

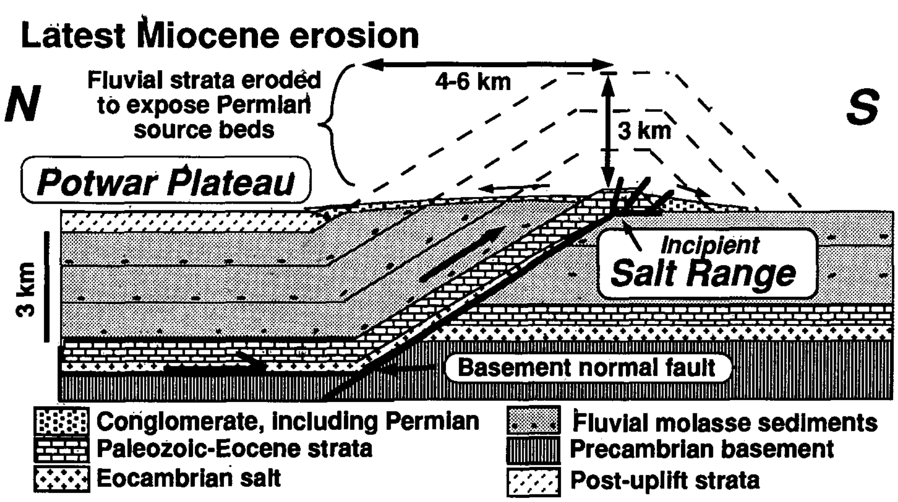

Figure 2. Reconstruction of stratal geometries along northern edge of Salt Range at ~5.4 Ma. Dashed lines depict geometry of fluvial strata in hanging wall that would have been uplifted above local base level. Most of these strata would have had to be removed in order to expose Paleozoic strata at erosional surface from whence clasts were transported into newly formed piggyback basin. Footwall cutoff corresponds to basement normal fault with ~1 km throw (Baker et al., 1988).

The main phase of Salt Range thrusting occurred ~4 m.y. later. Although perhaps surprising, this long interval of quiescence followed by reactivation of the Salt Range thrust is consistent with likely mechanical constraints on the developing thrust wedge (Moussouris and Davis, 1989). The initiation of this phase of thrusting is inferred from the documented cessation of sediment accumulation in the southern one-third of the Potwar piggyback basin. In the eastern Salt Range, deposition continued on both flanks of the present-day Kotal Kund syncline until <1.8–1.6 Ma (Frost, 1979; Johnson et al., 1982). Subsequently, ~15 km of additional shortening occurred as the allochthon ramped upward and advanced southward across the subhorizontal detachment underlying the present Salt Range (Fig. 3). Presumably, the entire 2.5–3 km thickness of foreland fluvial strata was either carried in the hanging wall across the Salt Range or partially eroded as it was carried to the crest of the ramp. Nearly the complete sequence of foreland fluvial strata has been stripped from the hanging wall. The minimum rate of denudation of this extensive area (>2000 km^2) has been 1.5–2 mm/yr during the past 1.8 m.y. The predominance of exposures of carbonate-rich strata in the present Salt Range suggests that these rocks erode at much slower rates than do the fluvial strata in this semiarid climatic regime.

Soan Syncline

The Soan syncline on the northern margin of the Potwar Plateau (Fig. 1) is an asymmetrical structure with a vertical northern limb (Fig. 4) and gently dipping southern limb that steepens toward the Riwat fault (Gill, 1952). Seismic data from the synclinal region (Baker et al., 1988; Pennock et al., 1989) suggest that an antiformal stack underlies the steep northern limb. Along this limb, a 6 km thickness of vertically oriented, Miocene-Pliocene fluvial strata extend nearly to the core of the syncline. The beds have been truncated along a subhorizontal unconformity and are overlain by the Lei Conglomerate (Fig. 4). Paleomagnetic data (Moragne, 1979; unpublished data) indicate that predeformational fluvial deposition continued beyond the end of the Gauss chron (2.48 Ma; Berggren et al., 1985). Extrapolation of accumulation rates from the Gauss chron to the youngest preserved strata below the unconformity suggests that they date from ~2.2 to 2.1 Ma. Magnetic and radiometric data from the overlying Lei Conglomerate (Raynolds and Johnson, 1985) indicate that the oldest postuplift strata slightly predate the beginning of the Olduvai subchron at 1.87 Ma. These chronological data define a deformational and erosional interval of 200–300 ka. Reconstructions (Fig. 4) indicate that the simplest geometry of the eroded hanging wall

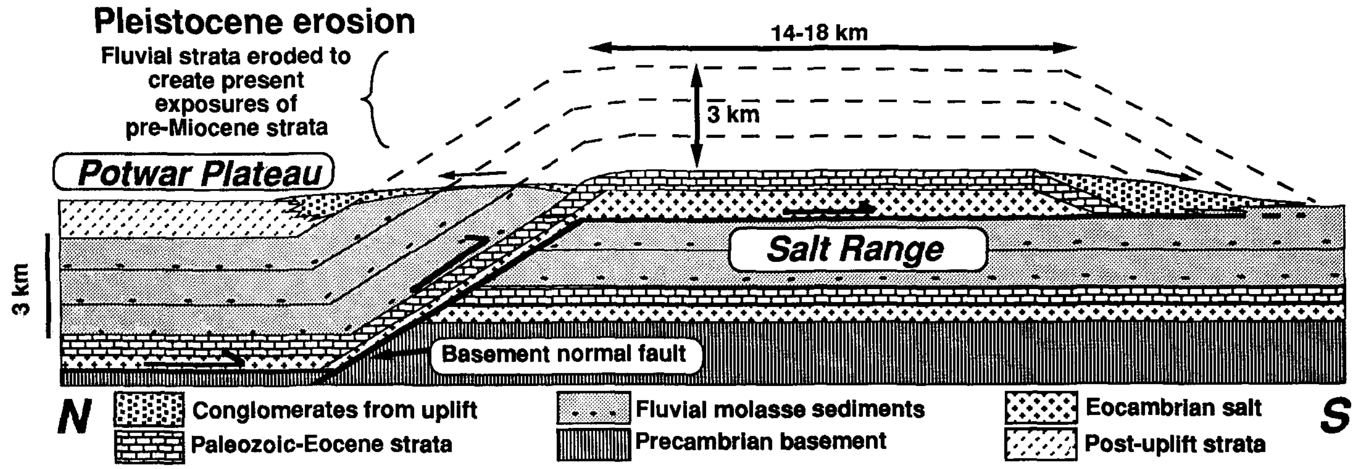

Figure 3. Schematic north-south cross section of Salt Range and southern Potwar Plateau at present. Dashed lines indicate stratal geometries of fluvial strata in overthrust hanging wall that have been erosionally stripped to expose Eocene and older strata across breadth of range. Geometry of hanging wall, including thick salt contained within it, are based on seismic and structural interpretation of Baker (1987).

requires an average of at least 3 km of uplift and denudation during this time span. This uplift does not refer to uplift of the mean erosional surface, which, as predicted by some recent models (England and Molnar, 1990), would have stayed at nearly the same elevation. Because the more northerly continuation of the Soan syncline strata is not preserved, it is not possible to ascertain whether a significantly greater volume of strata has been eroded than that estimated here. The volume of denuded material could be less than calculated if extensive bedding-parallel slip occurred in the northern limb of the syncline. However, the absence of significantly flattened magnetic inclinations or of structural indicators of shearing suggests that pure shear was not extensive. These data thus indicate a minimum rate of uplift and erosion of 10–15 mm/yr over this 200–300 ka interval. Although the aerial extent of denudation cannot be precisely defined, it exceeds 60 km^2 and may be more than 200 km^2.

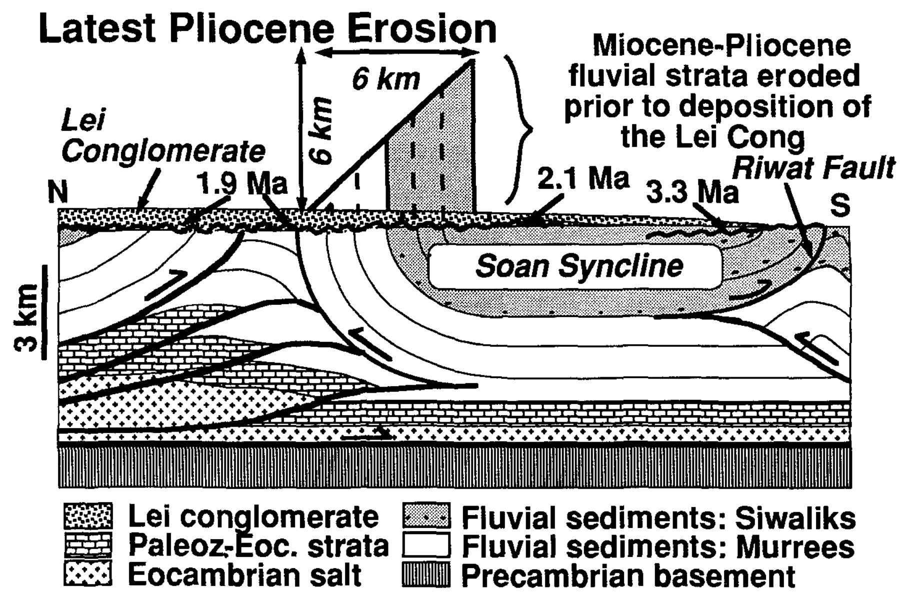

Figure 4. Schematic north-south cross section of Soan syncline at present. Structural interpretation based on Pennock et al. (1989). Various strata and unconformities have been dated from magnetostratigraphies and fission-track dating. Geometrically constrained, minimum cross-sectional area of uplifted fluvial strata that eroded between 2.1 and 1.9 Ma is shown.

DISCUSSION

These examples from the foreland basin of northern Pakistan provide unusually well-constrained intervals of erosion during which minimum rates of denudation ranging from 1.5 to 15 mm/yr were sustained for as long as 1.6 m.y., and rates at least as high as 10–15 mm/yr were sustained for 0.2–0.3 m.y. Although rates comparable to these minimal rates have been measured for some modern, relatively short term erosional processes over study areas of limited size (e.g., Scott and Williams, 1978), documentation of sustained high rates for >200 ka over broad areas (60 to >2000 km^2) is rare. Basin relief during these erosional episodes cannot be precisely determined. Given the present relief in actively uplifting areas of the Himalayan foreland, however, it is likely to have been considerably less than 30% of the total uplift. Because the calculated erosion rates are 5 to 20 times higher than those predicted (Ahnert, 1970) for the probable relief in the foreland, they have important implications for concepts concerning landscape development and the impact of newly imposed thrust loads on subsidence and sediment accumulation.

The central conclusion derived from these data is that the mean uplift rate was nearly balanced by the rate of denudation of uplifted fluvial strata. It should be noted that the degree of induration and cementation within the 3–6 km thickness of strata was only moderate. Given these conditions, little topography would have developed within a growing anticline or above an active thrust ramp. For forelands like those of the Himalaya, western Pyrenees, or Argentinian Andes, this implies that several kilometres of uplift could be accompanied by relatively subdued topography.

In settings where a thick fluvial succession overlies carbonate strata, high rates of erosion of the fluvial strata under arid and semiarid climatic conditions may influence the ultimate geometries of thrusts. For example, where a thrust ramps upward to the surface, initially the thrust tip would not necessarily advance significantly beyond the crest of the ramp. As long as fluvial strata were being carried up the ramp to the erosional surface, rapid denudation rates could nearly keep pace with the rate of shortening (De Paor and Anastasio, 1987). When the underlying hanging-wall carbonates were lifted to the erosional surface, however, the rate of denudation would drop dramatically. Any continued shortening would promote advance of the thrust tip across or very near to the synorogenic surface. Hence, in situations where the base of the advancing thrust can be lubricated sufficiently to overcome the mechanical resistance to advance, the thrust tip may migrate forward. This response apparently occurred in the Salt Range itself (Moussouris and Davis, 1989), where remobilized salt underlies the southernmost, 15–20-km-wide detachment (Fig. 3). Where the mechanical resistance to advance cannot be overcome (McElroy, 1990), the leading edge of the thrust is likely to undergo hindward imbrication, or continued shortening will be accommodated by development of new thrusts elsewhere. As pointed out by McElroy (1990), the hindward imbrication commonly seen along former tiplines across the southern Pyrenean foreland basins appears to represent this accommodation mechanism.

Recent forward-modeling studies of thrusting and sedimentation in foreland basins (e.g., Flemings and Jordan, 1989) have commonly modeled crustal-scale thrusts. The high rates of erosion of fluvial strata suggest that if these models were applied to the development of large, individual thrusts within foreland basins, they might need considerable modification. Whereas most models (e.g., Angevine et al., 1990) would predict that the rapid uplift of a 4–6-km-thick hanging wall would impose a significant new load on the crust and cause related subsidence, the rate data presented here suggest that if the hanging wall comprised primarily a thick carapace of fluvial strata, the magnitude of loading and subsidence produced would be greatly reduced. Although the depositional system would be profoundly rearranged by a significant new thrust, thrust-induced subsidence and hanging-wall topography would be a fraction of that predicted by most models. In the Salt Range of Pakistan and the External Sierras of the Pyrenees, for example, the accommodation space directly attributable to the thrust load would be expected to be ~75% less than that predicted for a hanging wall in which nearly the entire thickness was preserved during emplacement. If the eroded strata were deposited in the adjacent foreland, the subsidence caused by this distributed load (e.g., Flemings and Jordan, 1990) would partially compensate for the reduced subsidence resulting from the thinned thrust load. In the Himalayan foreland, however, transport of sediments through the basin is sufficiently prevalent that only a fraction of the eroded strata is ever deposited in the nearby foreland.

If other conditions are equal, variations in erodibility are a function of the interactions between climate and different rock types. Whereas in the Himalayan foreland fluvial deposits are more susceptible to erosion under the prevailing semiarid climatic regime, in a more humid setting carbonates might be eroded through dissolution more quickly than fluvial strata would be mechanically removed.

Finally, it should be noted that very high rates of denudation in the Himalayan region are not confined to the foreland basin. Perhaps the greatest vertical relief (7 km) in the shortest horizontal distance (21 km) in the world occurs at Nanga Parbat in northern Pakistan, where uplift at rates of ~5 mm/yr for the past 1–2 m.y. are implied by fission-track annealing dates (Zeitler, 1985). Given that the majority of this uplifted massif has been removed by erosion, the mean regional erosion rate here has averaged ~3–4 mm/yr during this interval. In this steep and largely alpine topography, numerous landslides and vigorous glacial erosion have helped sustain this rapid denudation rate, whereas in the foreland, it appears that fluvial erosion is the dominant denudational process.

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Notes