Climate-Driven Bedrock Incision in an Active Mountain Belt

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Measurements of fluvial bedrock incision were made with submillimeter precision in the East Central Range of Taiwan, where long-term exhumation rates and precipitation-driven river discharge are independently known. They indicate that valley lowering is driven by relatively frequent flows of moderate intensity, abrasion by suspended sediment is an important fluvial wear process, and channel bed geometry and the presence of widely spaced planes of weakness in the rock mass influence erosion rate and style.

The links between the tectonic uplift, climate, and denudation of an active mountain belt are forged in bedrock river channels (*1*, *2*). Fluvial incision of uplifted bedrock lowers the base level and drives mass wasting of adjacent hillslopes. The resulting debris is eventually deposited onto valley floors, where it enhances or impedes fluvial wear of the channel bed (*1–3*). Where fluvial wear does not check rock uplift, the region's relief, steepness, and orographic precipitation rates rise until steepened river slopes and enhanced discharge allow fluvial erosion to balance tectonic uplift once again.

The mechanics of fluvial wear are commonly considered in terms of average flow conditions and abrasion due to bedload transport (*1*, *4*, *5*), but few observations are available to validate these assumptions (*6–8*). The role of average versus extreme flows in producing erosion is unknown, as is the relative importance of abrasion and wear by particles in turbulent suspension. Here we present observations of fluvial bedrock incision due to moderate and extreme discharges from the LiWu River in the eastern Central Mountain Range of Taiwan (Fig. 1) to help address these questions. Originating at 3500 m above sea level, the LiWu River drains approximately 600 km^2 of steep terrain underlain by metasedimentary rocks. The area has high rates of tectonic uplift [3 to 6 km per million years (My^{-1})] and sediment yield, indicating strong forcing and the presence of natural tools for incision by abrasion (*9–12*). Approximately 10^7 metric tons of sediment move through the river each year, or about 0.1% of the global supply of sediment to the sea (*13*).

Daily hydrological records for the LiWu River span 40 years (*14*). Discharge during typhoons can exceed the long-term daily average by an order of magnitude or more. In August 2000, Supertyphoon Bilis produced a flood in the LiWu River (Fig. 2, A and B) peaking at 2240 m^3 s^{-1}, or about 65 times the daily average discharge of 36 m^3 s^{-1} from 1960 to 2001. Such floods have dramatically elevated sediment loads (*3*) (Fig. 2C). No sediment data are available for Supertyphoon Bilis, but from other available records for 1982 we estimate that approximately 90% of the total sediment discharge, and 15% of the total water discharge of that year, occurred over 5 days during a similar typhoon-driven flood (*14*). No major storms crossed the LiWu catchment during the dry season after August 2000 or in the following wet season of 2001 (Fig. 2A).

To document the ongoing incision of the LiWu River, we established a field site with representative channel geometry near the only gauging station in the catchment (Fig. 1). The upstream drainage area is 435 km^2, and the channel slope averaged over a 1-km reach spanning the site is 0.02. The continuously exposed bedrock at the site comprises schists and a prominent quartzite bed that runs across the channel (Fig. 1). These two lithologies dominate the upper catchment and have contrasting properties. The schists are densely foliated, and a conventional field measure (22 on a Schmidt hammer scale) (*15*) indicates low compressive strength; a single tensile strength test, using the Brazilian tension splitting method, yielded a value of 5.3 MPa. The quartzite is massive, with relatively continuous joints spaced at decimeter intervals, and exhibits intermediate compressive strength (Schmidt hammer scale 63) and a tensile strength of 9.5 MPa. The tensile strengths of both rock types are within the normal range for metasedimentary rocks (*8*). In an abrasion mill test, the schist was found to abrade approximately four times faster than the quartzite (*8*, *16*, *17*).

Our site covers most of the active channel of the LiWu River, which has a parabolic cross

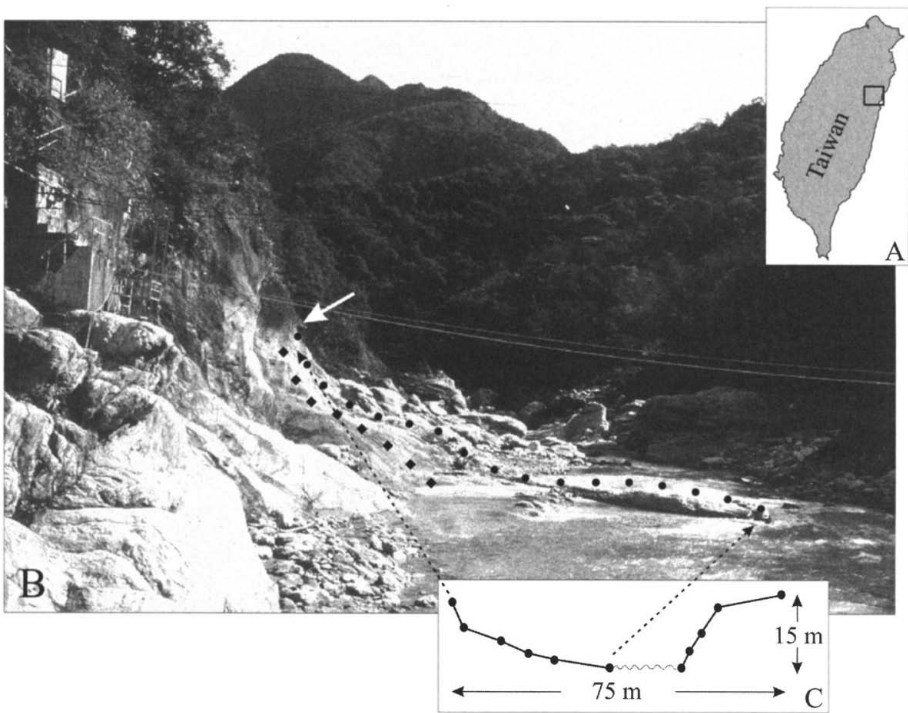

Fig. 1. (**A**) Location of study site within Taiwan. (**B**) Photograph of site from upstream. Black circles represent the location of transect drilled and measured on quartzite, and black diamonds represent the location of the schist transect. White arrow shows the high-water mark, approximately equivalent to the high point of Supertyphoon Bilis. The metal cage and overhead cables indicate the location of discharge and the suspended sediment gauging station. (**C**) Cross section of the channel along the quartzite outcrop with survey points, showing characteristic parabolic shape with steep side walls. The wavy line represents the low-water mark.

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section and a locally well-developed inner channel (Fig. 1C). The active channel is defined overall as the wetted perimeter of the maximal flood and is delimited by the lower margin of dense forest cover of adjacent hillslopes. From February 2000 to December 2001, we conducted four detailed surveys of channel bedrock elevation at 20-mm intervals, using an array of permanent, recessed, and evenly spaced benchmarks (Fig. 1B). Vertical erosion at a point is estimated as the change in bedrock topography incurred during an interval between surveys, with the understanding that most of the measured signal may be associated with one or a small number of exceptional discharge events. Standard errors of repeat measurements of bedrock topography along a reference transect well above the high-water mark indicate a precision of 0.5 mm or better. This level of precision did not vary within or between field seasons. We focus here on results from two survey transects oriented perpendicular to the channel to sample erosion at representative elevations between characteristic low- and high-water levels. One transect is 24 m in length in schist, and the other is 42 m long in quartzite. Together, these transects comprise 2109 measured points.

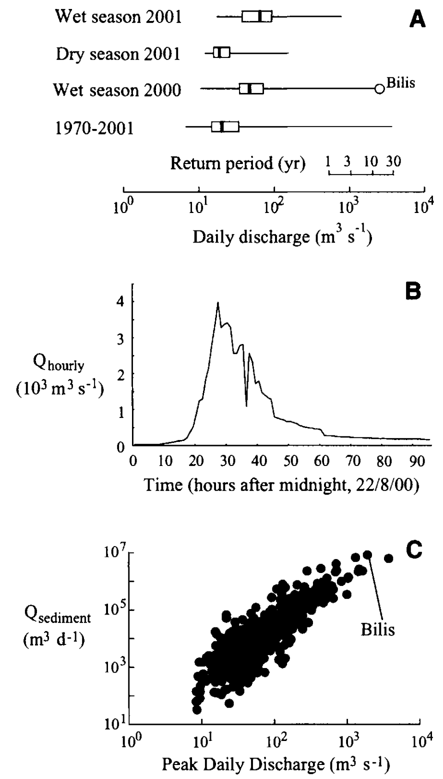

Fig. 2. (**A**) Box plot summarizing LiWu hydrology during indicated periods. The heavy vertical lines indicate median values, boxes enclose the central two quartiles, and whiskers indicate the full range of daily discharge values. The peak day-long discharge associated with Supertyphoon Bilis, in August 2000, is indicated by the open circle. Return period of exceptional floods shown for reference. (**B**) Hourly hydrograph of discharge (Q) at the field site associated with Supertyphoon Bilis, for 96 hours after midnight, 22 August 2000. (**C**) Sediment rating curve for all events observed in LiWu catchment from 1970 to 2001. Discharge and the predicted sediment discharge point for Supertyphoon Bilis are indicated.

Our surveys captured changes during an active typhoon season (the wet season of 2000), a dry season (the dry season of 2001), and a relatively inactive typhoon season (the wet season of 2001) (Fig. 2A). Median estimates of erosion across the active channel and for the entire period from February 2000 to December 2001 were 8.5 mm for the quartzite and 6 mm for the schist. However, important spatial and temporal patterns emerged during the course of our study, with maximal local erosion of 182 mm in quartzite and 69 mm in schist.

Erosion in both lithologies was greater, by up to an order of magnitude, during the wet season of 2000 than during the subsequent dry and wet seasons of 2001 combined (Fig. 3). Maximal values of spatially averaged erosion were 82 mm in the quartzite and 36 mm in the schist for the period between February and December 2000. In contrast, analogous values of erosion were 6 and 2 mm, respectively, for the period from December 2000 to December 2001.

Erosion peaked at higher elevations within the active channel during the 2000 wet season than during the dry and wet seasons of 2001. In particular, wear was greatest between 2 m and 6 m above mean low-flow level in the quartzite and between 3 m and 7 m above mean low-flow level in the schist. Above these elevations, spatially averaged wear of several millimeters occurred up to the flood line of Supertyphoon Bilis, at about 10 m above the mean low-flow level. Low in the channel, the erosion rate dropped significantly. In contrast, erosion during the 2001 dry and wet seasons mostly occurred less than 3 m above mean low-flow level, with wear rates increasing toward the low-flow line (Fig. 3).

High erosion rates in quartzite reflect to some degree its current relatively exposed aspect elevated above the schist (Fig. 1) and the effect of controls on erosion resistance, such as spacing and condition of joints, that are not captured by usual measures of rock strength (*8*). Rock mass properties contribute as controls on the style of erosion, with a greater spread and more irregular distribution of erosion in the broadly jointed quartzite than in the densely foliated schist (Fig. 3). As an example, a coefficient of variation for the spatial interval exhibiting maximal average erosion, and defined as the ratio of the range of observations in the central quartiles to the median of observations, is 1.04 for the quartzite during the 2000 wet season and 4 during 2001. The analogous values for schist were 0.58 and 1.0, respectively. The different values reflect an order of magnitude decrease of median wear rates between the wet season of 2000 and the wet and dry seasons of 2001, paired with only a twofold reduction of the range of wear rates in the central quartiles. We propose that the differences in the relative spread of wear rates are associated with the removal of joint-bound blocks, which are decimeters in size, from the quartzite. The removal of quartzite blocks is visible through before-and-after measurements of the topography (fig. S1) and was prominent at intermediate elevations in the channel where erosion rates were largest. In February 2000, these blocks were firmly lodged in the channel bed in locations with relatively little lateral support, and we suspect that fracturing was needed for their removal, in addition to hydraulic forces (*18*). Similar removal of blocks was not observed in the adjacent schists (fig. S1). Observed lithological and spatial differences in wear are consistent with the notion that, where and when active, the removal of blocks is a more effective style of fluvial bedrock erosion than abrasion (*2*, *4*, *18*).

In addition to block removal, we consider small-scale abrasion to be the likely cause of much erosion at intermediate flow levels during floods. Peak flow conditions during Supertyphoon Bilis (flow depth h = 12 m, channel slope s = 0.02) correspond to bed shear stress in excess of 2000 Pa, which is sufficient to move boulders with diameter d of up to 3 m as bedload. The average eleva-

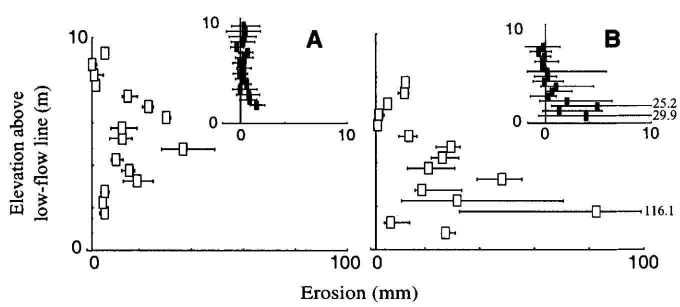

Fig. 3. Erosion rates for schist (**A**) and quartzite (**B**) through the typhoon 2000, dry 2001, and typhoon 2001 seasons. Boxes represent median values of erosion rates as a function of elevation above the low-flow line, and whiskers represent 25th- and 75th-percentile values. Elevation range has been divided into 50-cm intervals, and all measurements within an interval combine to produce the median values for that elevation. Open boxes represent the combined median values from the wet season of 2000, and inset black boxes represent combined median values from subsequent seasons, including the dry season and inactive wet season of 2001. Inset graphs have same axis labels as the larger graphs. Erosion rates represent vertical (downward) erosion at a point, not widening or horizontal values.

tion achieved by bedload particles can be given in terms of fractional depth Z_b and relative grain size $D = d/h$ by

$$Z_b = AD\theta^{1/2} \quad (1)$$

where $\theta = sh/Rd$ with $R = 1.65$ for quartz grains in water and the empirical dimensionless coefficient $A \approx 4$ for irregularly shaped particles (*19*). Thus, a meter-sized boulder would have bounced up to several meters above the bed during peak flood conditions. Sediment of this caliber is relatively rare in the LiWu channel, because the schists that dominate the upper catchment produce much finer debris. In extreme floods, such material would travel in turbulent suspension.

In a channel that is steep-walled and parabolic in cross section, the vertical distribution of particles suspended in simple channel flow can be described generally with a single expression (*20*). Mathematical averaging of this expression over the relative depth range $\{Z_b, 1\}$ yields the fractional depth Z_s, above which the concentration of suspended particles of a given size decays significantly from its near-bed maximum nominally taken at Z_b. Thus, Z_s is given by

$$Z_s = \frac{Z_b^P - Z_b}{(1 - P)(1 - Z)} \quad (2)$$

where $P = 2.5\ \theta^{-1/2}$ for medium sand and larger particles. From Eqs. 1 and 2, we find that only particles for which $P < 0.3$ (or $\theta > 70$) would have traveled in significant numbers at elevations greater than 0.3 h or, equivalently, at >4 m above the bed during peak flood. Such particles have diameters of about 2 mm or less. Thus, we propose that maximal wear rates at midlevels of peak flow are due to rare but significant impacts of large boulders saltating along the bed and to more or less continuous abrasion by very coarse sand and finer material in suspension transport.

Spatially averaged erosion of both rock types between December 2000 and December 2001 approached values of 2 to 6 mm year^{-1} and occurred near the base of the channel. These incision rates are in good agreement with independent estimates of long-term exhumation at 3 to 6 mm year^{-1} mentioned above. During the 2000 wet season, in contrast, spatially averaged wear of both rock types locally exceeded 10 mm to a significant degree, with maximal values observed at greater elevations on the channel wall. This work is assumed to be predominantly a result of Supertyphoon Bilis, because other floods failed to reach that high in the channel. The return period for events equal to or greater than Supertyphoon Bilis is estimated to be about 20 years (Fig. 2A) (*14*). Prorated for this frequency, the maximal spatially averaged erosion rates for the 2000 wet season were 5.5 mm year^{-1} for quartzite and 2.3 mm year^{-1} for schist, but corresponding values for the base of the channel were only 1.7 mm year^{-1} for quartzite and 0.3 mm year^{-1} for schist. This suggests that erosion rates associated with exceptional events fail to balance estimates of long-term exhumation rates throughout the active channel. Our data indicate that the lowering of the LiWu valley is driven by relatively frequent flows of low to moderate intensity (*21*) and that rare large floods are more important in widening the bedrock channel than they are in driving down the base level. However, such floods help transmit the effect of accumulated thalweg lowering to adjacent hillslopes.

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Fig. S1

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Uplift in the Fiordland Region, New Zealand: Implications for Incipient Subduction

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Low-temperature thermochronometry reveals regional Late Cenozoic denudation in Fiordland, New Zealand, consistent with geodynamic models showing uplift of the overriding plate during incipient subduction. The data show a northward progression of exhumation in response to northward migration of the initiation of subduction. The locus of most recent uplift coincides with a large positive Bouguer gravity anomaly within Fiordland. Thermochronometrically deduced crustal thinning, anomalous gravity, and estimates of surface uplift are all consistent with ~2 kilometers of dynamic support. This amount of dynamic support is in accord with geodynamic predictions, suggesting that we have dated the initiation of subduction adjacent to Fiordland.

The response of plate boundaries to the initiation of subduction remains a fundamental, unsolved problem in plate tectonics (*1*). Geodynamic models of subduction initiation generally predict the plate over a newly descending slab will be dynamically uplifted during the first few million years after the initiation of convergence (*1*, *2*). The rate of uplift will be proportional to the rate of convergence whereas the amount of uplift will be proportional to the amount of total compression, at least during the early phase of subduction nucleation (*1*). As a consequence of this dynamic support or uplift, a strong positive gravity anomaly would develop on the overriding plate as the base of the crust is progressively uplifted over time.

The apparently young plate boundary adjacent to the Fiordland region of South Island, New Zealand, along with its offshore

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