New constraints on sediment-flux–dependent river incision: Implications for extracting tectonic signals from river profiles

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ABSTRACT

We present new field data from rivers draining across active normal faults that incise across the same lithology at the fault, have been subjected to similar climatic regimes and tectonic settings, and were perturbed by a well-documented increase in fault slip rate ca. 1 Ma. In spite of these similarities, the rivers exhibit markedly different long profiles and patterns of catchment incision. We use channel slope and hydraulic geometry data for each river to calculate bed shear stresses (τ_b), and show that there is no simple relationship between peak τ_b and the relative uplift rates across the faults, *U*, which differ by a factor of four. The long-term average sediment supply to each channel (Q_s), estimated from time-averaged catchment erosion rates, can explain the τ_b versus *U* data if bedload modulates bedrock incision rate, *E*, in a strongly nonlinear way. Together these field data allow us, for the first time, to evaluate theoretical predictions of the role of sediment on river profile evolution and to quantify the magnitude of the effect in natural systems.

Keywords: geomorphology, erosion, transient response, faulting.

INTRODUCTION

It is well recognized that a key control on landscape response in mountainous terrains is the rate of incision in bedrock rivers because it sets the rate of base-level lowering for hillslope processes. Several models for bedrock incision have been published that differ mainly in their treatment of sediment transported by the river. These models make very different predictions about the scale, morphology, and rate of landscape response to climatic and/or tectonic forcing (e.g., Whipple and Tucker, 2002). A key challenge has been to find effective ways of discriminating between these models and calibrating successful models using appropriate field observations. Whipple and Tucker (1999) argued that a powerful way to elucidate the underlying physics of fluvial processes is to study systems that are undergoing a transient response. This idea has been pursued (e.g., van der Beek and Bishop, 2003), but results have been equivocal because details of the external forcing are insufficiently constrained, or the temporal evolution of the transient behavior is not well characterized, or factors, such as sediment supply to the channel, have not been quantified. Here we address this challenge by comparing four rivers draining across active normal faults in southern Europe for which the uplift patterns are independently well constrained, and the climatic regime and bedrock lithology are essentially the same. Our constraints on the relative uplift rate, *U*, where the river crosses the fault, enable us to evaluate the ability of published fluvial incision models to explain our field data. The most successful model is one in which pebbles transported by the rivers modulate bedrock incision rate, *E*, by varying the amount of plucking and/or abrasion versus coverage of the channel base depending on the relative sediment supply (e.g., Sklar and Dietrich, 2004). Our data also indicate that pebble lithology as well as volume of sediment play key roles in controlling *E*. We quantify the magnitude of the effect using *U* at the river outlet to derive relative fluvial efficiency, plus catchment-averaged erosion rates to estimate long-term sediment supply relative to transport capacity. Thus we derive new constraints on this phenomenon for natural systems over geologic time scales.

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STUDY AREAS AND METHODS

Figure 1 summarizes the structural positions, catchments and long profiles of four rivers draining across active normal faults in central Italy and mainland Greece (GSA Data Repository Fig. DR1[1]). Both areas are within a Mediterranean climatic regime in a narrow latitude range (38–42°N), where climatic variations over the past ~0.5 m.y. have been similar (Tzedakis, 2005). The maximum offsets on the faults are comparable (2–3 km), as is fault spacing (10–12 km). In both study areas, extension initiated in the Pliocene (Roberts and Michetti, 2004; Roberts and Jackson, 1991) and footwall uplift exposed Mesozoic platform carbonates with a Selby rock mass strength of ~60 (Whittaker et al., 2007b). Extension is accommodated by fault segments with systematic variations in throw and throw rate from the segment center to the fault tips (e.g., Cowie and Roberts, 2001). Consequently, a different uplift rate affects each river, but incision keeps pace with faulting, because no scarps are preserved in any of the channels.

Throw rates along active faults in central Italy (Fig. 1A) over the past 3 m.y. are constrained by structural mapping, biostratigraphy, and

[1]GSA Data Repository item 2008139, Figures DR1–DR2 and Table DR1, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

tephrachronology (e.g., Roberts and Michetti, 2004). These data show that ca. 0.7–1.0 Ma the Fiamignano fault increased its throw rate from ~0.3 mm/yr to 1.0 mm/yr near the segment center where the Rio Torto drains across the fault (Fig. 1A; Whittaker et al., 2007a). Where the Torrente L'Apa crosses near the fault tip, the throw rate similarly increased ca. 1 Ma from ≤0.1 mm/yr to 0.25 mm/yr (Fig. 1A). Relative uplift rate, U, which controls base level, tracks this throw rate variation (Whittaker et al., 2007b).

The constraints on throw rates along the Knimis-Arkitsa fault system, Greece (Fig. 1B), come from the distribution of Pliocene–Pleistocene strata, which accumulated close to sea level in the Gulf of Evia. The uplift of these marine and/or lacustrine sediments to present-day elevations of 500–800 m in the footwall of the Knimis fault occurred as the throw rate increased ca. 1 Ma, when a strike-parallel fault array to the south became inactive (Goldsworthy and Jackson, 2001; Cowie et al., 2006). The timing of fault acceleration coincided with fault segment linkage between the Knimis and Arkitsa faults, resulting in the uplift of the lacustrine and/or marine sediments to an elevation of ~300 m in the linkage zone (Roberts and Jackson, 1991). The Xerias River drains across the area where the faults linked. The present-day footwall uplift rate at the fault, relative to sea level, is U = 0.3–0.5 mm/yr; prior to linkage the river exploited the gap between the two faults, i.e., $U \approx 0$ mm/yr (Fig. 1B). The Voagris River drains across the western tip of the Knimis fault where U, inferred from incised 125 ka river terraces, is <0.2 mm/yr (Goldsworthy and Jackson, 2001).

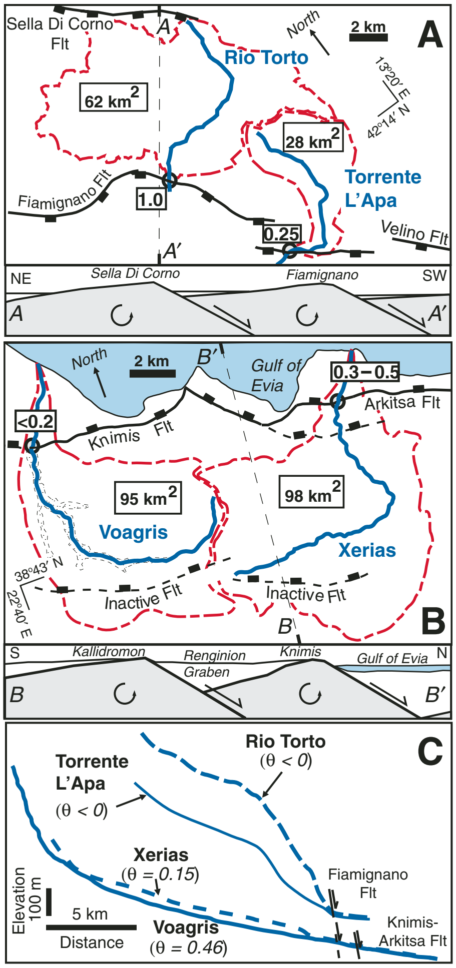

Figure 1. Four studied catchments. A and B: Map views with structural cross sections below. C: River long profiles. Derived from 20 m digital elevation models and field mapping. Drainage area (km²) and uplift (*U*, mm/yr) indicated at catchment outlets. In C, θ indicates concavity obtained from slope-area analysis. Flt—fault.

OBSERVATIONS

In spite of the similarities in tectonic setting, climate, and bedrock lithology, the four rivers have markedly different long profiles (Fig. 1C). The channels from central Italy have long profiles that are clearly convex immediately upstream of the Fiamignano fault; channel slope, S, ranges from 8% (Torrente L'Apa), where the present-day relative U = 0.25 mm/yr, to >10% where U = 1.0 mm/yr (Rio Torto). In contrast, the long profile of the Xerias River (mainland Greece), which crosses the Arkitsa fault where U = 0.3–0.5 mm/yr, has a low concavity, $\theta \approx 0.15$ (i.e., $S \sim A^{-0.15}$, where A is area), upstream of the fault and $S \approx$ 2.0%–4.5%. Farther west along the Knimis fault, where U <0.2 mm/yr, the long profile of the Voagris River shows a concave shape typical of equilibrium rivers and no change in gradient at the fault. These data show no simple functional relationship between S and U, or between θ and the spatial variation in uplift rate upstream of the faults.

The first-order difference between these four rivers is that the Voagris is a typical alluvial river with an active alluvial plain several hundreds of meters wide and no bedrock exposed, whereas the Torrente L'Apa, Rio Torto, and Xerias River are all actively incising into bedrock upstream of the fault, carving dramatic slot gorges. To further compare the three bedrock rivers, measurements of high flow channel width, W_b, depth, H, and local channel slope, S, were collected using a laser range finder (see Whittaker et al., 2007b, for details). These data were used to calculate downstream variations in high flow bed shear stress, $\tau_b = \rho_w gRS$, where ρ_w is density of water, g = 9.81 ms^{-2}, and hydraulic radius $R = W_b H/(W_b + 2H)$. High flow depth, H, estimated from scour marks and vegetation contrast, is assumed to represent a stage with a moderate (1–10 yr) recurrence interval. Median grain size D_{50} was obtained from Wolman point counts on active pebble bars at ~100 m intervals and used to derive Shields stress, $\tau^* = \rho_w RS/[(\rho_s - \rho_w)\ D_{50}]$, where ρ_s is grain density. We also estimated fraction of bed area exposed and thickness of the alluvial veneer.

We estimate clear water stream erosivity by calculating τ_b, thus taking into account differences in drainage area and hydraulic geometry (via R) between the three catchments. In Figure 2 we project normalized stream-wise distance onto a line oriented orthogonal to the active fault and compare τ_b with relative uplift rate. The flexural wavelength in these study areas is similar to fault spacing (~10 km), so a linear decrease in rock uplift rate across the footwall can be assumed (Anders et al., 1993). The Rio Torto and Torrente L'Apa both show increasing τ_b downstream in response to increasing U toward the Fiamignano fault, and an abrupt decrease in τ_b on the hanging-wall side (Fig. 2). Where these two rivers cross the fault U differs by 4×, due to the lateral variation in throw rate, but the peak τ_b values differ by only 1.5× (~1800 Pa compared to ~1200 Pa). Also, the upstream extent of the τ_b peaks is less than half the width of footwall uplift, indicating that topographic steady state has not been reached in the upper part of these catchments (Whittaker et al., 2007b). In contrast, the Xerias River shows a much smaller peak in τ_b (~500 Pa), even though U = 0.3–0.5 mm/yr is bracketed by the rates at the two Fiamignano localities. Moreover, the peak in τ_b is offset ~2 km upstream of the Arkitsa fault, and there is no systematic increase in τ_b toward the fault, so another mechanism must enhance the erosivity to match the downstream increase in U.

A key difference (Fig. 3; Fig. DR2) between the three bedrock rivers is that the upper reaches of the Xerias River (Fig. 3) are incising into Pliocene–Pleistocene fluvial conglomerates, deposited prior to fault acceleration, that contain pebbles of ophiolitic material and chert that are more resistant to erosion than limestone (Attal and Lavé, 2006). These pebbles are transported as bedload and cause impact abrasion and plucking of the limestone bedrock, even though there is significant (>80%) bedrock cover by pebble

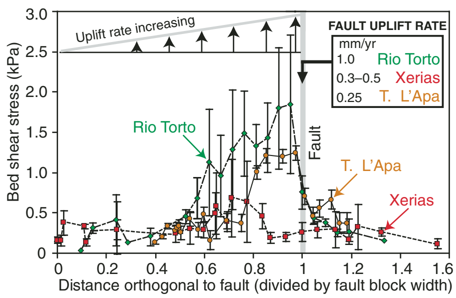

Figure 2. Bed shear stress as function of normalized distance upstream of the fault for three bedrock rivers shown in Figure 1. Error bars indicate standard deviation of reach scale averages obtained by channel surveying.

bars at low flow. In contrast, 50%–100% of the bedrock is exposed in the channels crossing the Fiamignano fault (Whittaker et al., 2007b), and the grains are predominantly limestone in composition, delivered to the channel by landslides from hillslopes above the gorges proximal to the active fault.

Even though all three catchments were subjected to an increase in U ca. 1 Ma, the landscape response is clearly also very different (Fig. 3). The spatial extent of vertical incision upstream of the fault since the throw rates increased is defined by area $A' \leq A$, where A = total drainage area (Fig. 3A). Only the lowermost parts of the Rio Torto and Torrente L'Apa catchments have been incised since 1 Ma, evidenced by the extent of angle-of-repose hillslopes and landslide debris upstream of the Fiamignano fault compared to unincised channels in the headwaters (Whittaker et al., 2007a). The boundary delimiting A' in these catchments is a hillslope break such that $A' \approx 0.1–0.2\ A$. The Xerias catchment, in contrast, shows incision across much of the total drainage area, i.e., $A' \approx A$, and numerous landslides supply hillslope material directly into the channel along its entire length (Fig. 3C). The difference evidently arises because the Pliocene–Pleistocene strata in the Xerias catchment are more easily eroded than the limestone bedrock that predominates in the Italian catchments.

DISCRIMINATING BETWEEN RIVER INCISION MODELS

Where active tectonic processes advect bedrock toward the surface, the erosivity of clear water flow is often assumed to control incision rate (detachment limited model; Howard et al., 1994). This model predicts a linear relationship, at steady state, between U, channel slope, and τ_b at the fault (e.g., Whipple and Tucker, 1999), which is inconsistent with our data (Fig. 2). By including an erosion threshold $\tau_{critical}$, a nonlinear relationship is predicted (e.g., Snyder et al., 2003), but a lower value of $\tau_{critical}$ would be implied by the low gradients along Xerias, at odds with uniformity in both bedrock lithology and D_{50} of transported grains in all three catchments (Fig. 3).

Material transported by a river directly influences E either through enhanced erosion of exposed bedrock, via impact abrasion and plucking, or via inhibiting erosion by limiting the amount of bedrock exposed, i.e., the "tools-versus-cover" effect (e.g., Sklar and Dietrich, 2004). A modified version of the stream power model allows for the magnitude of this effect via a function $f(Q_s)$, where Q_s is the volumetric rate of sediment supply (Fig. 4):

$$E = f(Q_s)KA^mS^n. \quad (1)$$

K is an erodability parameter, and the exponents m and n depend on whether bed shear stress or stream power drives incision (Whipple and Tucker, 2002). If both tools and coverage effects are important, $f(Q_s)$ is expected to follow a parabolic-like function of Q_s/Q_c, where Q_c is transport capacity. The linear decline model (Beaumont et al., 1992), in contrast, assumes that the coverage effect is the main control (Fig. 4).

We estimate the relative magnitude of $f(Q_s)$ for Rio Torto, Torrente L'Apa, and the Xerias River by inserting values for A and S at the fault into equation 1, and eliminate K by comparing river pairs with different E; the absence of scarps in the channels implies that $U = E$ at the fault. The ratio Q_s/Q_c depends on hillslope processes and rates, plus changing hydrologic conditions for which we do not have a complete record over geologic time. Qualitative information on long-term Q_s/Q_c is provided by the ratio A'/A, which is the proportion of each catchment that is being actively incised compared to the

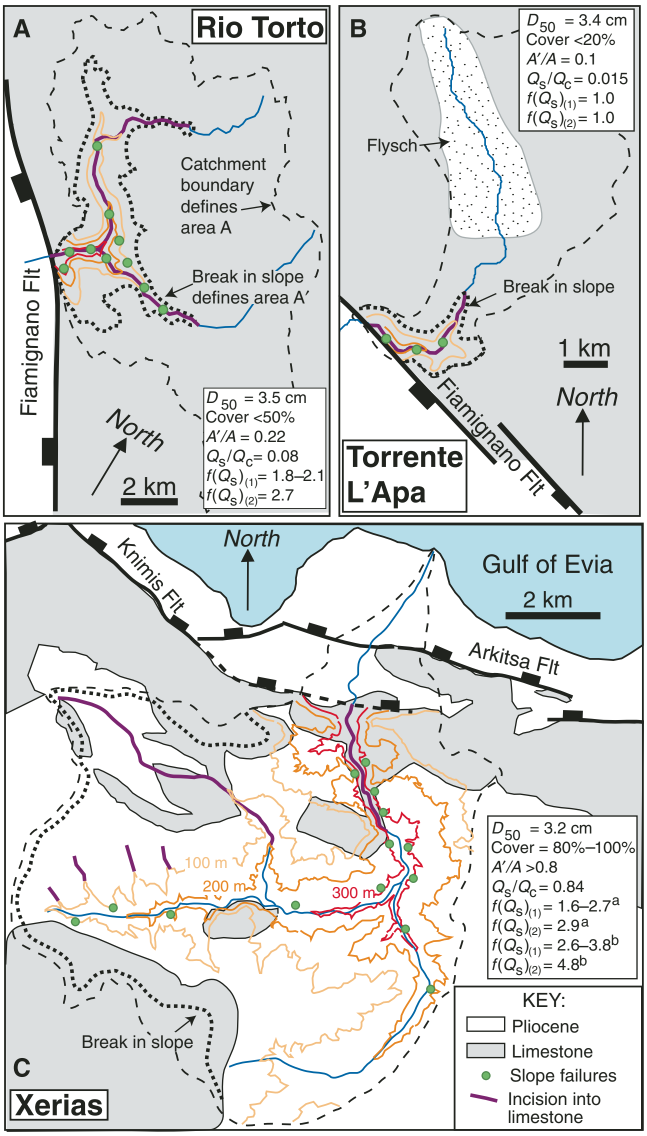

Figure 3. Maps of catchment incision. A: Rio Torto. B: Torrente L'Apa. C: Xerias River. Contours of total vertical incision since ca. 1 Ma are shown by contours labeled in C. Incised area = A'; total catchment area = A. Slope failures are indicated by green dots. Tabulated data show median grain size D_{50}, percent bed cover, relative sediment supply, Q_s/Q_c, and from equation 1: $f(Q_s)_{(1)}$ using hydraulic scaling; $f(Q_s)_{(2)}$ using measured τ_b: a = 0.3 mm/yr; b = 0.5 mm/yr, lower and upper bounds on Arkitsa throw rate (Table DR1; see footnote 1). Flt—fault.

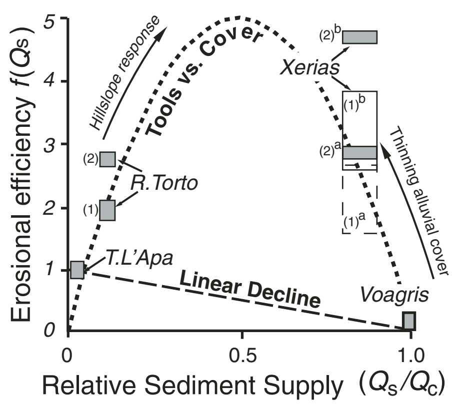

Figure 4. Diagram comparing theoretical models to field data (see Fig. 3; Table DR1 [see footnote 1]). T.—Torrente; R.—Rio.

total area that potentially receives precipitation (Fig. 3): for larger A'/A, the fraction of channel bed exposed is smaller (Table DR1). We also calculate average erosion rate over the area A' since 1 Ma for each catchment to derive a time-averaged estimate of Q_s (in m^3/yr) and compare it to Q_c, estimated using the transport equation $Q_c = pAS$ (p = average runoff rate assumed to be uniform and the same for all catchments).

Torrente L'Apa, the most undersupplied river, is assigned the reference value $f(Q_s) = 1$, to which the other bedrock rivers are compared. The increase in Q_s/Q_c in the Rio Torto relative to Torrente L'Apa (Fig. 3) arises because the higher incision rate near the fault segment center has driven a greater proportion of the hillslopes above threshold. The corresponding increase in $f(Q_s)$ allows the Rio Torto to keep pace with the 4× higher uplift rate even though τ_b has only increased by 1.5×. The relatively high sediment supply ($Q_s >> 0.5Q_c$) in the Xerias River arises because, in response to fault acceleration, it evolved from an alluvial channel comparable to the Voagris into a bedrock channel by steepening, narrowing, and consequent erosion of the alluvial cover. Xerias still carries a significant load, but $\tau^* = 0.4$–1.5, i.e., well above threshold for transport-limited conditions (Mueller et al., 2005). The high value of $f(Q_s)$ obtained for Xerias explains its lower gradient at the fault (Fig. 3). Voagris represents the end-member case: $Q_s/Q_c = 1$, $f(Q_s) = 0$, as it is not incising into bedrock.

These results are consistent with the tools-versus-cover model of Sklar and Dietrich (2004) and clearly at odds with constant $f(Q_s)$ and the linear-decline model (Fig. 4). The contrast in lithology between the Pliocene pebbles and the limestone bedrock in the Xerias probably also contributes to its high $f(Q_s)$ value. Specifically, limestone pebbles are much less abrasive than igneous and metasedimentary pebbles when interacting with limestone bedrock (Sklar and Dietrich, 2001; Whittaker, 2007). The falling limb (cover effect) of the parabolic model is deduced from the fact that if sediment supply along the Xerias River increases, the alluvial veneer would accumulate to a point where it is no longer incising into bedrock, i.e., $f(Q_s) \rightarrow 0$.

CONCLUSIONS AND IMPLICATIONS

This study demonstrates that average sediment supply to a channel over time scales of 10^4–10^6 yr is of first-order importance in controlling river long profile evolution. Our field data are most consistent with theoretical models in which incision rate is enhanced by the availability of abrasive tools when $Q_s << Q_c$, but ultimately limited by the fraction of bed area exposed when $Q_s >> Q_c$, (e.g., Sklar and Dietrich, 2004). Compared to a shear stress erosion model, we find that the sediment effect is equivalent to an ~3–5× increase in τ_b.

Channel convexities upstream of a fault are often cited as evidence for recent tectonic activity, and channel steepness indices are used to infer spatial variations in relative uplift rate (e.g., Kirby and Whipple, 2001). This study is the first field calibration of theory (e.g., Sklar and Dietrich, 2006), which predicts that variations in Q_s/Q_c can obscure any simple correlation between channel slope and tectonics. Neglecting this effect may result in an active fault being interpreted as inactive or its relative uplift rate being significantly underestimated.

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