Role of river incision in enhancing deformation

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ABSTRACT

Many active compressional belts contain examples of transverse rivers intersecting anticlines at their highest structural and topographic position. This unusual association between rivers and doubly plunging anticlines at relatively small scales is usually explained by some form of antecedence or superposition. In this article I suggest an alternative explanation, i.e., that river erosion unloads the crust and that this process causes local deformation to be enhanced in the vicinity of rivers. I show the plausibility of this hypothesis with the aid of a coupled three-dimensional mechanical-surface process mathematical model. The conclusion is that river incision can have a major influence on deformation of the surrounding crust if incision occurs at the same time that the crust is deforming plastically in response to regional compression. In this case, incision amplifies background deformation at a relatively small scale, leading to the formation of noncylindrical folds with culminations coinciding with river incision. In the absence of regional deformation, the response of the crust to river incision is small and of long wavelength because it is governed by flexural isostasy of relatively rigid elastic crust. Thus, whether rivers exert an influence on local deformation depends critically on the timing between river incision and regional deformation. This point may explain why in some cases, rivers appear to have had no significant influence on local deformation, whereas in other cases, they have.

Keywords: deformation, erosion, river incision, domes, folding, FEM modeling.

INTRODUCTION

Although it is now generally recognized that erosion has an important influence on deformation in orogenic belts, uncertainty persists regarding both the nature of erosion-deformation coupling and the spatial scale at which this coupling ceases to become important. This uncertainty is reflected in debate concerning the influence of localized river incision on deformation and uplift of the surrounding crust (Molnar and England, 1990; Montgomery, 1994). On the one hand, the crust is viewed as being relatively weak (due to plastic behavior) and in a state of near-isostatic equilibrium, which implies that river incision could lead to significant local deformation (e.g., Davis et al., 1983; Koons, 1994). On the other hand, the crust is envisaged as being elastic and relatively rigid, which implies that most river valleys would have a small or negligible influence on deformation of the surrounding crust because of their short-wavelength nature (e.g., Turcotte and Schubert, 2002). Most investigated field examples have been argued to fall into the "strong-crust" class (e.g., see Small and Anderson, 1998; Gilchrist et al., 1994; Leonard, 2002). Notable exceptions are the large rivers transecting the eastern and western syntaxes of the Himalayas; these rivers have been inferred to play a major role in explaining the spatial coincidence of rapid erosion, high topography, and the location of young metamorphic massifs (Zeitler et al., 2001; Finlayson et al., 2002; Koons et al., 2002). This coincidence has been explained by a conceptual model whereby exhumation beneath the rapidly eroding rivers causes hot weak rock to be advected close to the surface; this leads to positive feedback, thus enhancing rock uplift, erosion, and exhumation (Koons et al., 2002). If one is to accept this "tectonic aneurysm" model, then several questions immediately arise. First, why are more examples not observed wherein there is a spatial and temporal coincidence between river incision and localized deformation, and second, how is this model consistent with evidence that the crust is, at least initially, relatively strong and thus resistant to localized erosion, at least when stress is first applied? The purpose of this paper is to suggest answers to these two questions.

I begin by pointing out that there are numerous (though largely ignored) examples of rivers transecting doubly plunging anticlines (termed here anticline domes) in fold-and-thrust belts that are interpreted as reflecting erosion-enhanced deformation. In the second part of the paper I show, with the aid of a three-dimensional (thin plate) mechanical numerical model, how such structures can be formed and how they are consistent with both the strong-crust and weak-crust cases described above.

EXAMPLES OF TRANSVERSE RIVERS INTERSECTING ANTICLINE DOMES

One of the most remarkable features of drainage networks in active fold-and-thrust belts that appears to have been largely ignored in recent years is the common occurrence of transverse rivers cutting the axial culmination of anticlines (Fig. 1). Oberlander noted that "what is conspicuous in the Zagros orogen is the uncanny homing instinct of the larger streams, which find all the anticlines they can, while open structural spillways often gape on either side," and "could it be a mere

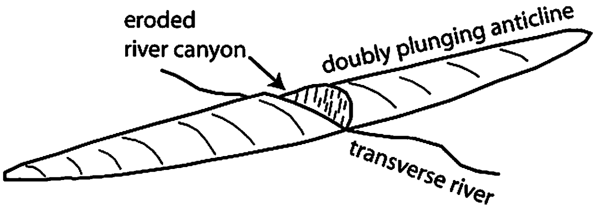

Figure 1. Schematic diagram showing transverse river intersecting axial culmination of doubly plunging fold structure, a feature observed in many fold-and-thrust belts. This structure is interpreted here to result from erosion that unloads crust and enhances background deformation in vicinity of river.

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coincidence that this also appears true of the streams in different regions of the Himalayas noted by Bordet, Gansser, Birot, and Valdiya? Or is there a general tendency for streams in fold-and-thrust belts (including folded overthrusts) to be attracted to cross-grained structural highs?" (Oberlander, 1985, p. 173). Casual observation of geologic and topographic maps shows that apparently similar relationships between transverse rivers and structural highs (many of which were noted by Oberlander, 1985) can be found in the Pyrenees (e.g., the Segre River at the Oliana anticline), the Swiss Alps (e.g., the Rhone below Martigny, the Reuss above Lake Lucerne, the Linth and Wallensee in the vicinity of Glarus), the French Alps (the Chérin River above Cusy and Val de Fier), the Himalayas (Arun and Karnali Rivers, in addition to the syntaxes), and the central Andes (e.g., the Azapa and Luta Rivers near Arica). The most recent well-documented example of transverse rivers cutting anticline domes is in the central Apennine fold-and-thrust belt (Alvarez, 1999).

ORIGIN OF RIVER-TRANSECTED ANTICLINE DOMES

The close association between transverse rivers and anticline domes is not predicted by simple conceptual models invoked to explain drainage patterns in fold-and-thrust belts (e.g., Burbank et al., 1996), whereby rivers, although anticipated to transect actively growing structures, should not do so in the position of greatest structural and topographic relief. Recognizing this, several explaining mechanisms have been proposed. For example, Oberlander (1985) suggested that the association between transverse rivers and anticline domes in the Zagros could be explained by a combination of superposition and antecedence in a sequence containing resistant limestone formations separated by large amounts of easily erodible flysch-like sedimentary rock. However, as pointed out by Alvarez (1999), the sedimentary sequence required for such a mechanism to work does not exist in the Apennines despite the observation of structures very similar to those found in the Zagros. Other Apennine workers have noted the coincidence of transverse rivers and transverse faults, particularly in axial culminations (see Alvarez, 1999). However, such an observation is also consistent with the mechanism whereby river incision localizes deformation. As stated in the introduction, this model (i.e., erosion-enhanced deformation) has gained popularity for explaining the spatial coincidence of metamorphic massifs and transverse rivers in the Himalayan syntaxes, but has been largely neglected as a possibility elsewhere (however, see Mussuridis et al., 1992; Norris and Cooper, 1997; Pavlis et al., 1997). One reason for this neglect may be that, according to the tectonic aneurysm model, deformation is envisaged to be largely facilitated by thermal weakening. Although this rationale may be true for the Himalayan syntaxes where high-grade metamorphic rocks have been rapidly exhumed to the surface, the mechanism is not viable for smaller-scale structures where the depth of exhumation is on the order of a few kilometers at most (typical of fold-and-thrust belt structures). Another reason that the river erosion–induced deformation model is typically neglected is the short-wavelength nature of river erosion that is typically shown using elastic models to exert a small, long-wavelength isostatic-flexural response. However, as I show in the next section, this prediction changes when one considers the potential for plastic deformation and the possibility that the crust is deforming in response to regional compression contemporaneously with river incision.

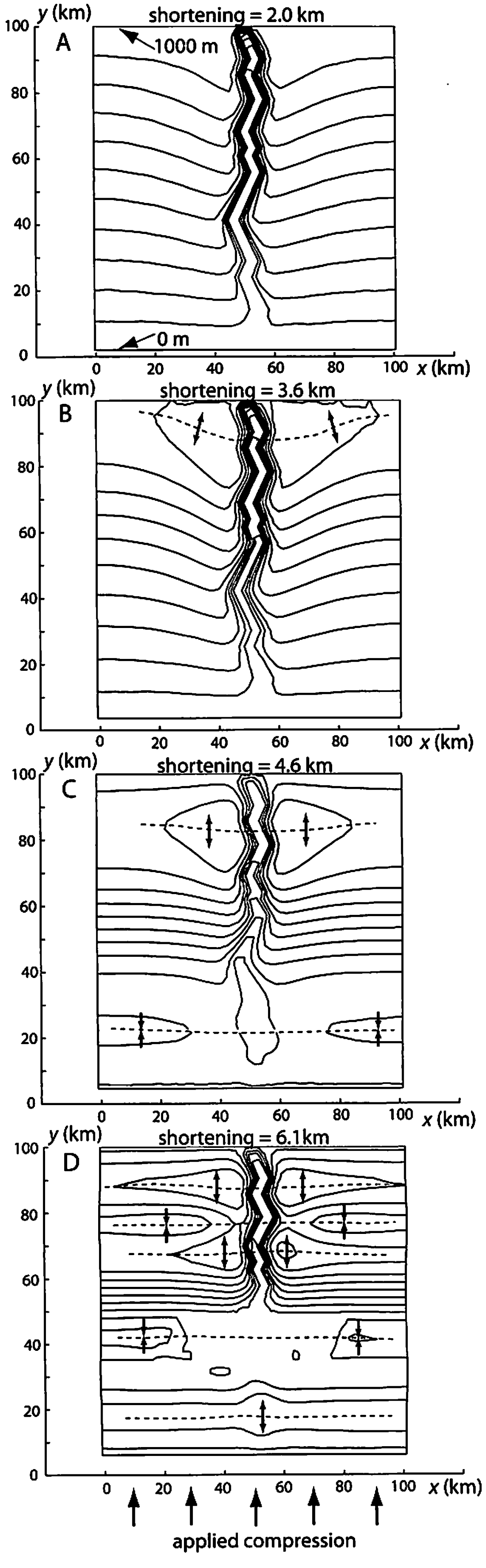

Figure 2. Calculated topography for elastic-plastic plate compressed in y-direction and subjected to localized river incision. A–D: Topography after 2.0, 3.6, 4.6, and 6.1 km of shortening, respectively. Initial topography has slope of 0.01. Because model domain is 100 × 100 km, this slope implies that upper boundary has elevation of 1000 m. Note that folds developed during compression are noncylindrical because of influence of river incision on deformation.

MODEL FOR EROSION-INDUCED FORMATION OF ANTICLINE DOMES

I have performed a series of finite element numerical calculations in order to test whether the spatial coincidence between anticline domes and transverse rivers may be due to erosion-enhanced deformation. The mechanical part of the model is a three-dimensional elastic-plastic (von-Mises) thin plate that includes both bending and in-plane deformation and that overlies an inviscous (i.e., very weak) substrate (Simpson, 2004). The erosion-deposition model is that of Simpson and Schlunegger (2003), and is modified here to include a quasi-kinematic description of river incision. Although the results presented are intended to be general in nature, I have chosen a model setup to be most applicable to a fold-and-thrust belt setting. Accordingly, I consider a 100 × 100 km spatial domain that has a constant regional slope of 1%. Compression (constant velocity) is applied along the lower boundary in a direction perpendicular to the regional slope, while the upper boundary is blocked from deforming in this direction. A single localized river is initiated on the sloping surface by kinematically specifying a fixed discharge inlet at the approximate center of the upper boundary. The discharge is then free to flow down the surface. In addition, I assume that there is an influx at each position down the drainage network that is equal to the boundary influx. Thus, the river discharge increases linearly downstream. This approach crudely mimics a localized river that is being progressively recharged in the downstream direction either by tributaries or by springs. This simple erosion model enables one to focus on the influence caused by a single river, which is not generally possible in nature because the river spacing is typically narrower than the zone that may be influenced by erosion-induced deformation. The following parameters were used in the calculations presented: plate thickness = 10 km, Young's modulus = 1×10^{11} MPa, Poisson's ratio = 0.3, yield strength = 100 MPa, density of inviscous substrate = 2700 kg·m^3, density of eroding or depositing material = 2300 kg·m^3, boundary-convergence rate = 0.02 m·yr^{-1}, uniform rainfall = 0 m·s^{-1}, water influx = 0.01 m^2·s^{-1}, hillslope diffusivity = 6.3×10^{-7} m^2·s^{-1}, fluvial erosion coefficient = 0.01 s·m^{-2}, and fluvial erosion exponent = 2. The erosion-related parameters have been chosen simply to ensure that the river is able to maintain its course across a typical growing structure, which is a necessary condition for structure-transverse rivers. A uniform distribution of random noise with an amplitude of 1 m was applied to both the topographic surface and the plate midplane. This distribution serves to initiate deformation and to ensure that discharge flows down the surface in a slightly tortuous path. Additional boundary conditions for the plate are free lateral boundaries and simple support boundaries in the direction of loading. Boundary conditions for the surface topography are fixed upper and lower boundaries and zero sediment flux across the lateral boundaries.

Results of three different simulations are considered. In the first simulation, regional compressional deformation is applied during river incision. In the second simulation, river incision occurs in the absence of regional compression. In the third simulation, regional compression is applied in the absence of river incision. Apart from these differences, all model parameters are the same in each case.

Results of the first numerical simulation—in which an elastic-plastic plate is deformed by regional horizontal compression during localized river incision—are presented in Figure 2. Initially, discharge flowing down the surface causes the incision of a deep (<1 km deep) river canyon (Fig. 2A). Although the unloading related to incision induces a component of flexural-isostatic uplift localized in the vicinity of the river, the magnitude of this uplift is small and is thus barely distinguishable from the background slope. After ~3.5 km of convergence (Fig. 2B), the elastic-plastic plate begins to buckle and, after further convergence, forms a fold (i.e., an anticline and syncline pair) with a wavelength equal to the shortened plate length (i.e., ~95 km; Fig. 2C). These folds, rather than being cylindrical, are doubly plunging with culminations coinciding with the river. After even more deformation, the initially formed folds break up into shorter-scale structures with wavelengths of ~20 km (Fig. 2D). The reason for this switch to shorter wavelength deformation is poorly understood, but appears to be related to both stress relaxation caused by folding and to the formation of plastic fold hinges, which essentially decouple the limbs of the initially produced folds. The combined result is that each initial fold limb becomes refolded at a wavelength equal to the length of the limb. Once again, the produced folds are noncylindrical and their culminations coincide with the location of the river. This simulation indicates that localized river incision has a major influence on deformation in the surrounding crust.

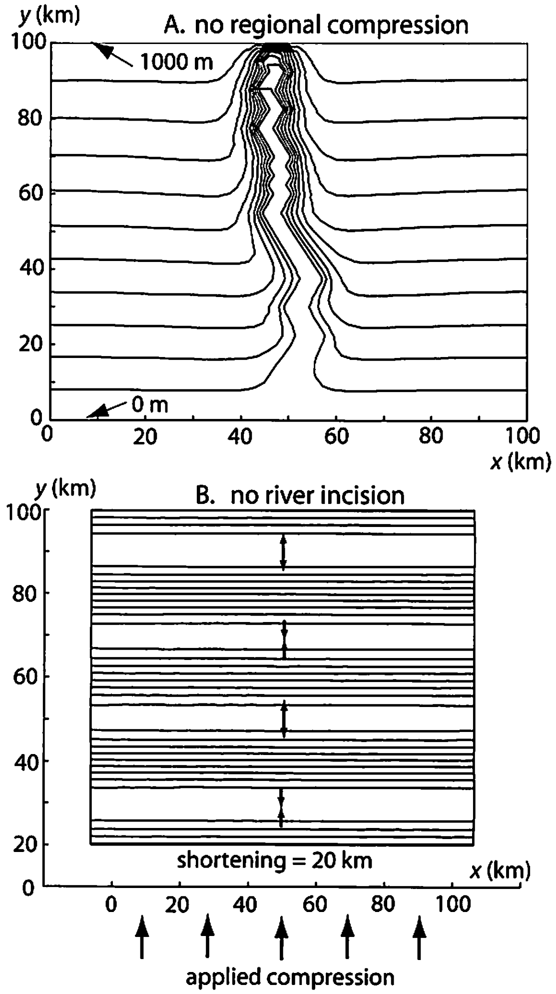

Figure 3. A: Influence of river incision on deformation is drastically reduced if there is no background regional deformation. In this case, even though river has incised deep valley (with maximum relief of ~800 m), isostatic-flexural uplift (~60 m) is barely distinguishable on regionally sloping topography. B: Regional deformation in absence of river incision generates cylindrical folds (shown here after 20 km of shortening). These folds are initiated after much greater shortening (~18 km) than when river incision is considered (~3.5 km). Thus, river incision greatly facilitates folding.

Results of the second simulation where river incision occurs in the absence of regional compression are presented in Figure 3A. Note that because regional compression is excluded, all deformation is caused by river incision and is related to flexural-isostatic bending of the elastic-plastic plate. In this case, one observes that although unloading caused by river incision generates flexural-isostatic rebound, the magnitude of this uplift (~60 m) is barely distinguishable from the background topography (Fig. 3A). Results of the third simulation in which regional compression is applied in the absence of river incision are presented in Figure 3B. In this case, buckling takes place much later than the deformation in the presence of erosion (after ~18 km of shortening; Fig. 3B). Moreover, the resulting folds are purely cylindrical with wavelengths of ~40 km. Comparison of this simulation with that presented in Figure 2 indicates that river incision has a major influence on the deformation of the elastic-plastic plate.

Simulations carried out with different parameter values show the same broad features as the results presented in Figures 2 and 3, but differ in the details. For example, reducing the plate thickness (or decreasing the plastic yield stress) reduces the wavelength of deformation and the length scale over which erosion influences deformation. Only when deformation of the plate is purely elastic (e.g., if the plastic yield stress is very high) does erosion cease to have any significant effect on deformation. Results are also insensitive to the exact position of the river and are not strongly influenced by the lateral boundary conditions.

CONCLUSIONS

One of the purposes of this study has been to bring attention to a remarkable feature of drainage networks in active fold-and-thrust belts that appears to have been largely overlooked in recent years, i.e., the common occurrence of transverse rivers cutting the axial culmination of anticlines. I suggest that such features do not result from chance, but form because large rivers unload the crust, and this process tends to amplify the background deformation and lead to the formation of noncylindrical (doubly plunging) structures at relatively small scale. This hypothesis has been verified with the aid of a coupled erosion-mechanical model. Simulations reveal that river incision can have a major influence on deformation of the surrounding crust in fold-and-thrust belt settings. However, in order for river incision to be important, the crust must be deforming plastically in response to regional deformation. In this case, river incision enhances the background deformation by facilitating folding, especially in the local vicinity of the river. This behavior results in a train of doubly plunging anticline and syncline folds transected at axial culminations by a river. In comparison, deformation in the absence of river incision is characterized by development of cylindrical structures that are initiated after significantly greater amounts of shortening than in the presence of incision. If river incision occurs in crust not subject to regional deformation, the response induced by erosion is flexural-isostatic in origin and probably too small to be observed in nature. Moreover, because stresses are lower in the absence of regional deformation, the crust behaves largely elastically, and the deformation response to erosion has a much longer wavelength. Thus, whether rivers exert an influence on local deformation depends critically on the timing between river incision and regional deformation. This point may explain why some observations indicate that river incision has had very little influence on deformation (Gilchrist et al., 1994; Small and Anderson, 1998), whereas other observations show that rivers have had an important influence (e.g., Norris and Cooper, 1997; Pavlis et al., 1997).

The proposed mechanism whereby rivers amplify regional deformation operates at relatively small scale (owing to the plastic nature of the deforming rocks) and results not from flexural isostasy, but from the ability of erosion to reduce the influence of gravity (which normally inhibits deformation) and to amplify background deformation. This mechanism is significantly different from the tectonic aneurysm model of Koons et al. (2002) that operates at relatively large scale and results from rheological weakening associated with exhumation and advection of hot weak rocks close to the surface. I anticipate that the mechanism proposed in this study will initially amplify deformation, and that if deformation remains localized for significant periods of time, the driving mechanism will progressively switch to one related to rheological weakening.

Finally, this study indicates that sediment-routing systems developing in fold-and-thrust belt settings must be viewed as reflecting two-way coupling between surface processes and the deforming substrate and not just in terms of interactions between local base-level variations and the rates of fluvial incision and aggradation.

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