THE UNIVERSITY *of* EDINBURGH

GEOMORPHOLOGY Rivers split as mountains grow

Citation for published version:
Attal, M 2009, 'GEOMORPHOLOGY Rivers split as mountains grow' Nature Geoscience, vol. 2, no. 11, pp. 747-748. DOI: 10.1038/ngeo675

Digital Object Identifier (DOI):
10.1038/ngeo675

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Nature Geoscience

Author Final Draft or ‘Post-Print’ Version. The final version was subsequently published in Nature Geoscience of the Nature Publishing Group (2009).
Cite As: Attal, M 2009, 'GEOMORPHOLOGY Rivers split as mountains grow' *Nature Geoscience*, vol 2, no. 11, pp. 747-748.

Subject strapline: **Geomorphology**
Title: **Rivers split as mountains grow**

Mountain landscapes are shaped by tectonics and climate. A series of laboratory experiments has documented a mechanism by which mountain river networks split as the geometry of a mountain evolves in response to an orographic precipitation gradient.

In mountainous landscapes the organization of fluvial networks is not random. Valleys tend to be evenly spaced[1] and, at the front of mountain ranges, the spacing of the drainage basin outlets is a direct function of the distance between the main drainage divide and the front of the range[2,3]. Numerous studies have focused on explaining why such geometrical properties emerge as landscapes develop under given tectonic or climatic regimes[1]. However, little is known about the mechanisms that modify the organization of fluvial networks in response to a change in climate or tectonics. On page 766 of this issue, Bonnet[4] identifies a mechanism that helps maintain these geomorphic laws: the number of drainage outlets along the dry side of mountain fronts increases when mountain geometry is altered by a precipitation gradient in a regime of tectonic uplift.

Rivers are the most important agents that shape non-glaciated mountainous landscapes: rivers incising into bedrock drive gravitational instabilities, thus controlling landsliding and other hillslope erosion processes[5]. Rivers also transport sediment from eroding mountains to the adjacent sedimentary basins (Figure 1), thus ensuring that rock and sediment mass will be transferred and distributed throughout tectonically active zones. The arrangement of river valleys obeys scaling laws that are mostly dependent on the nature of the material exposed and on climate[1]. Erosional processes have been shown to be responsible for this self-organization[1], but the mechanisms that lead to the modification of a well established fluvial network in response to changes in forcing are poorly understood.

As mountains grow, they form barriers for atmospheric circulation and generate a contrast in climatic conditions on either side the main drainage divide[6]. As a result, erosion rates are expected to become higher on the wet side than on the dry side, leading to the migration of the main divide towards the dry side[7]. This migration of the drainage divide has the effect of shortening the dry side, that is, decreasing the distance between the mountain peaks and the front of the mountain range. At the same time, the wet side of the mountain range lengthens. Because the distance between the front of the range and the divide controls the outlet spacing at the front of the range[2,3], the number of outlets on either side of the range should adjust to a migration of the divide. On the wet side, which widens with respect to the mountain peaks, the number of outlets should decrease, probably through mechanisms of drainage cannibalism (e.g. river capture)[8]. However, no mechanism had been documented so far that could increase the number of outlets at the front of the narrowing (dry) side of the range.

Documenting and identifying such mechanisms and reconstructing the erosion history of natural mountain belts, however, are difficult tasks; evidence tends to be removed through erosion itself. Fragments of information remain in the form of fluvial terraces in uplifted areas and sediments in depositional areas, but the temporal and spatial resolution of these records is rarely high enough to detect geologically short-lived events such as drainage reorganization. Carefully designed laboratory modelling experiments, although containing inherent simplifications that preclude the direct extrapolation of results to natural settings[4], offer the opportunity to reconstruct the complete evolution of landscapes and increase our understanding of the dynamics of this evolution.

Using such an experimental approach, Bonnet[4] shows that an initially symmetric mountain range undergoing constant tectonic uplift becomes asymmetric when a precipitation gradient is applied across the range, as expected from previous numerical modelling studies[7]. As predicted by the law of outlet spacing[2,3] the number of outlets increased on the drier side of the range. But the process by which the number of outlets increased was unexpected: the migration of the drainage divide caused the river channels themselves to split, a mechanism Bonnet has termed drainage splitting. The split channels then form networks draining smaller, more numerous drainage basins, keeping the expected relationship between the drainage divide-mountain front distance and the number of drainage outlets (Fig. 1a).

Bonnet's work not only newly identifies this mechanism of drainage reorganization, it also highlights key diagnostic morphological and sedimentological features associated with drainage splitting: unusual channel configurations, sediment perched on ridges and changes in fan sedimentation (Fig. 1) can document changes in the shape of mountain ranges. They may also be used to infer whether changes in climate, tectonics or rock type caused the modification of the mountain range.

The model does, of course, have limitations: the position of the front of the range is pinned and the rainfall gradient is smooth, whereas deformation fronts can usually migrate and changes in precipitation rate are usually sharp over natural drainage divides[6,9]. Nevertheless, Bonnet has recognized some of his key diagnostic features of drainage reorganization along the dry side of the Sierra Aconquija range of Argentina. The presence of these features in a natural environment thus supports the mechanisms revealed by the model. This agreement led Bonnet to suggest that the rainfall gradient over the range, which was previously shown to have developed as the mountains rose[10], led to a shift in the location of the drainage divide and subsequent drainage splitting.

The implications of this drainage splitting mechanism and the subsequent increase in the number of outlets at the range front are important. Sediment from more proximal sources will be deposited in smaller but more numerous fans closer to the mountain front, modifying the architecture of the sedimentary basin (Fig. 1a). More importantly, this mechanism will strongly modify the distribution of mass in the zone of mountain building (Fig. 1). The steepening of the mountain slope means that the bulk of the range will get closer to the front of the range on its dry side; however, the increase in drainage density at the front will reduce the height of the ridges and thus unload the front itself (Fig. 1b). In the sedimentary basin, the sediment load will be focused in a narrower zone close to the front of the range. Such load redistribution can potentially affect the location of the zones of active deformation, faulting and seismic activity within the mountain range[11,12].

In his study, Bonnet[4] shows that river channels can split in response to a shift in drainage divide towards the mountain front. The identification of this mechanism of drainage splitting lays ground for further investigations that will illuminate feedbacks between climate, fluvial network development, rock and sediment mass distribution and mountain building.

REFERENCES:

1. Perron, J. T., Kirchner, J. W., & Dietrich, W. E. *Nature* **460,** 502-505 (2009).
2. Hovius, N. *Basin Res.* **8,** 29–44 (1996).
3. Talling, P. J., Stewart, M. D., Stark, C. P., Gupta, S. & Vincent, S. J. *Basin Res*. **9,** 275–302 (1997).
4. Bonnet, S. *Nature Geosci.* **2,** XXX-yyy (2009).

5. Burbank, D. W. *et al. Nature* **379,** 505-510 (1996).
6. Roe, G. H. *Annu. Rev. Earth Planet. Sci.* **33,** 645–671 (2005).
7. Roe, G. H., Montgomery, D. R. & Hallet, B. *J. Geophy. Res.* **108,** 2315 (2003).
8. Bishop, P. *Progress in Phys. Geog.* **19,** 449-473 (1995).
9. Bookhagen, B. & Burbank, B.W. *Geophys. Res. Lett.* **33,** L08405 (2006).
10. Kleinert, K. & Strecker, M. R. *Geol. Soc. Am. Bull.* **113,** 728-742 (2001).
11. Simpson, G. D. H. *J. Geophys. Res.* **109,** F03007 (2004).
12. Simpson, G. D. H. *Basin Res.* **18,** 125–143 (2006).

Mikael Attal is at:
School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, Scotland, UK

FIGURE CAPTION:
Figure 1: Drainage splitting. **a**, When a precipitation gradient develops over a mountain range (left), the drainage divide (dashed line) will migrate towards the drier side of the mountain (right). As the divide migrates, the number of drainage outlets on the dry side of the range will increase. Bonnet[4] demonstrates that this increase occurs through the splitting of river channels, which increases the number of drainage basins. Furthermore, the rivers draining these basins deposit sediment eroded from the mountain-side in smaller fans that extend over a narrower zone close to the mountain front. **b**, Near the mountain front, the increase in drainage density driven by drainage divide migration leads to a reduction in the height of the ridges, as seen in profiles G to G' and H to H', and thus results in crustal unloading.