NATURE|Vol 460|23 July 2009

GEOMORPHOLOGY

Landscape texture set to scale

Kelin X. Whipple

Why, in many landscapes, does ridge–valley spacing show such regularity? The combination of high-resolution data and an elegant model offers a solution to this long-standing puzzle, for some cases at least.

The dissection of topography into ridges and valleys sets the scene for all manner of processes — physical, chemical and biological — that operate on Earth's surface. How do these processes interact to set the scale of this dissection? Although many other aspects of landforms seem to be scale-invariant[1], there are plenty of instances in which our own eyes tell us that ridges and valleys are uniformly spaced (Fig. 1) — that there is a fundamental scale to landforms. This impression can be confirmed quantitatively[2].

For more than a century, geomorphologists have recognized that valley spacing is probably governed by a transition from hillslope (unchannelled) soil transport to channelled stream incision. Hillslope soil transport acts in a diffusive manner and tends to fill in incipient channels cut by stream flow, and competition between these two processes has long been thought to determine the scale of landscape dissection. Much progress has been made[3–6], but no general theory with demonstrably predictive power has emerged — until now, that is, for Perron *et al.*[7] (page 502 of this issue) show that the wide variation in ridge–valley spacing can be explained by a simple model of this competition in a certain class of landscape.

From a scaling analysis of a statement of the conservation of mass, in previous work Perron *et al.*[6] derived a non-dimensional quantity, akin to a value called the Péclet number, that gauges the competition between soil creep and channel incision. Their numerical simulations demonstrated that this non-dimensional quantity does indeed, in principle, govern valley spacing.

In their latest paper, Perron *et al.*[7] test this model against observations using newly available, high-resolution topographic data[8] that reveal a tenfold variation in valley spacing among five field sites. To define a simple, testable hypothesis, they restrict their analysis to 'low-relief, soil-mantled' landscapes, where soil creep and stream flow are the dominant processes controlling sediment transport and erosion. For these cases, their model and scaling analysis predict that valley spacing scales with the ratio of the intensity of soil creep to the intensity of channel incision (D/K in their notation), but interestingly not with the actual erosion rate — a prediction in close agreement with previous theoretical work[4,5]. Perron *et al.* have developed a new method that allows the D/K ratio to be estimated directly from topographic data. They find a more than 60-fold variation in D/K among the field sites in different climatic and geological settings that correlates strongly with independently measured valley spacing in a manner consistent with model predictions.

But what sets the ratio of intensities of soil creep and channel incision (D/K)? Both the denominator and the numerator in this ratio are known, qualitatively, to depend in various ways on substrate properties, climate, hydrology and biota. However, the linkages among these factors as they co-evolve are notoriously complex. As yet no theory exists to predict how D/K should vary with climate or rock type, and new data are needed to guide fresh thinking.

Nonetheless, despite some scatter, the data used in this study[7] do provide some clues. They suggest that weaker rocks and drier climates are associated with closely spaced valleys (channel incision dominant), whereas stronger rocks and wetter climates are associated with widely spaced valleys (soil creep dominant) (Fig. 2). These findings are striking, in two respects.

First, although it is the less robust indication, the hint of a climatic control is interesting because the direct dependence of the intensity of channel incision on runoff[4,5] intuitively implies the opposite trend — that wetter climates would be associated with lower D/K and more closely spaced valleys. However, greater vegetative cover and increased soil disturbance by vegetation or animals can reduce runoff while accelerating soil creep[9].

Second, the tenfold difference in D/K ratio, and associated fivefold difference in valley spacing, between two of the field sites — Dragon's Back and Gabilan Mesa (Fig. 1) — is surprising. The sites are separated by only about 100 kilometres, experience a similar climate and are cut into the same moderately consolidated sedimentary rocks. These rocks seem to be slightly weaker at Dragon's Back, consistent with the general trend between rock strength and valley spacing. Dragon's Back is also slightly drier, and this climatic difference

J. T. PERRON

Figure 1 | Uniformity in ridge–valley spacing. This is Gabilan Mesa, California, one of the five 'low-relief, soil-mantled' sites that provided data for Perron and colleagues' analysis[7]. The valleys are cut into moderately consolidated sediments, with the distance between them being about 160 metres.

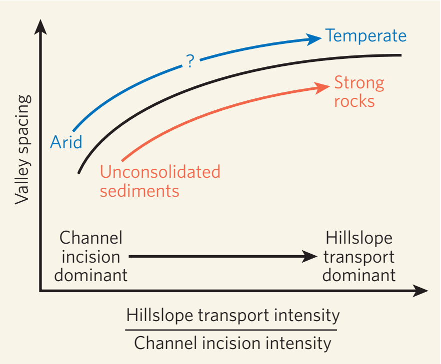

Figure 2 | Tentative interpretation of geological and climatic influences on valley spacing. According to theory, valley spacing in low-relief, soil-mantled landscapes is set by the ratio between hillslope transport (soil creep) intensity and channel incision intensity[4–7]. Perron and colleagues[7] provide a successful test of theory, and their data contain further hints about the underlying controls exercised by the substrate and climate: weaker rocks and (less certainly) drier climates seem to lead to a dominance of channel-incision processes and more closely spaced valleys.

is associated with a change from semi-arid grassland to oak savannah. Could these small differences be sufficient to explain the five-fold difference in valley spacing, or are other factors at play?

Much remains unknown about the complex controls on the intensity of soil creep and channel incision. But the work by Perron and colleagues[7] will encourage further investigation because their ratio seems to set the fundamental length scale in landscapes, and also suggests a method for quantifying rate constants for both creep and incision. The analysis has limitations, as the authors acknowledge. It is restricted to low-relief, soil-mantled landscapes, where landslides, earth flows and debris flows do not occur; it does not account for a threshold for channel incision[4,5]; and it is applicable only to quasi-steady-state conditions, in which erosion rate is approximately constant in space and time. Other considerations that merit attention are how temporal variations in rock uplift or climate change, over millennial to 100,000-year scales, may influence either topographic estimates of D/K or the relationship between D/K and valley spacing.

Despite these limitations, Perron *et al.*[7] have provided a powerful tool for further exploration. It promises to help deliver additional discoveries about the complex interactions between the physical, chemical and biological processes acting on the land surface. ■

Kelin X. Whipple is in the School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287-1404, USA.
e-mail: kxw@asu.edu

1. Rodríguez-Iturbe, I. & Rinaldo, A. *Fractal River Basins: Chance and Self-Organization* (Cambridge Univ. Press, 2001).
2. Perron, J. T., Kirchner, J. W. & Dietrich, W. E. *J. Geophys. Res.* doi:10.1029/2007JF000866 (2008).
3. Smith, T. R. & Bretherton, F. P. *Wat. Resour. Res.* **8,** 1506–1529 (1972).
4. Howard, A. D. *Earth Surf. Process. Landf.* **22,** 211–227 (1997).
5. Tucker, G. E. & Bras, R. L. *Wat. Resour. Res.* **34,** 2751–2764 (1998).
6. Perron, J. T., Dietrich, W. E. & Kirchner, J. W. *J. Geophys. Res.* doi:10.1029/2007JF000977 (2008).
7. Perron, J. T., Kirchner, J. W. & Dietrich, W. E. *Nature* **460,** 502–505 (2009).
8. National Center for Airborne Laser Mapping. www.ncalm.org.
9. Fernandes, N. F. & Dietrich, W. E. *Wat. Resour. Res.* **33,** 1307–1318 (1997).