How much do fractures matter? Erodibility as a function of lithology

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1. Introduction

Lithology and its influence on rock mass strength exert a first order control on landscape evolution by affecting the ability of rivers to erode into bedrock, determined by fluvial erodibility. Despite the many methods of testing and measuring rock mass strength, understanding and quantifying the impact of such properties on rates of surface processes and landscape forms remains a major challenge. Numerical models that describe river erosion through bedrock often use the stream power model, in which the erosion rate at any particular point in a bedrock river channel is defined by:

$$E = KA^m S^n \quad \text{(Eq. 1)}$$

where *K* is erodibility which is affected by rock strength, *A* is drainage area and *S* is river channel slope (Whipple & Tucker 1999). If spatial variability in uplift/erosion is low, *K* is expressed in channel slope (*S*).

However, discontinuities may complicate the relationship between rock strength and erosion: if fracture development affects the ease of erosion, then how much does the original strength of the rock matter? Tectonic history may affect erodibility through its control on fracture development, overprinting the role of intact rock strength.

2. Approach and results

Here, we assess the extent to which lithology controls fluvial erodibility through its control on rock strength in the High Atlas Mountains (NW Africa), where the geological age of bedrock and the associated duration of tectonic history in the mountain belt increases from east to west. In this setting bedrock contains discontinuities along lithological boundaries,

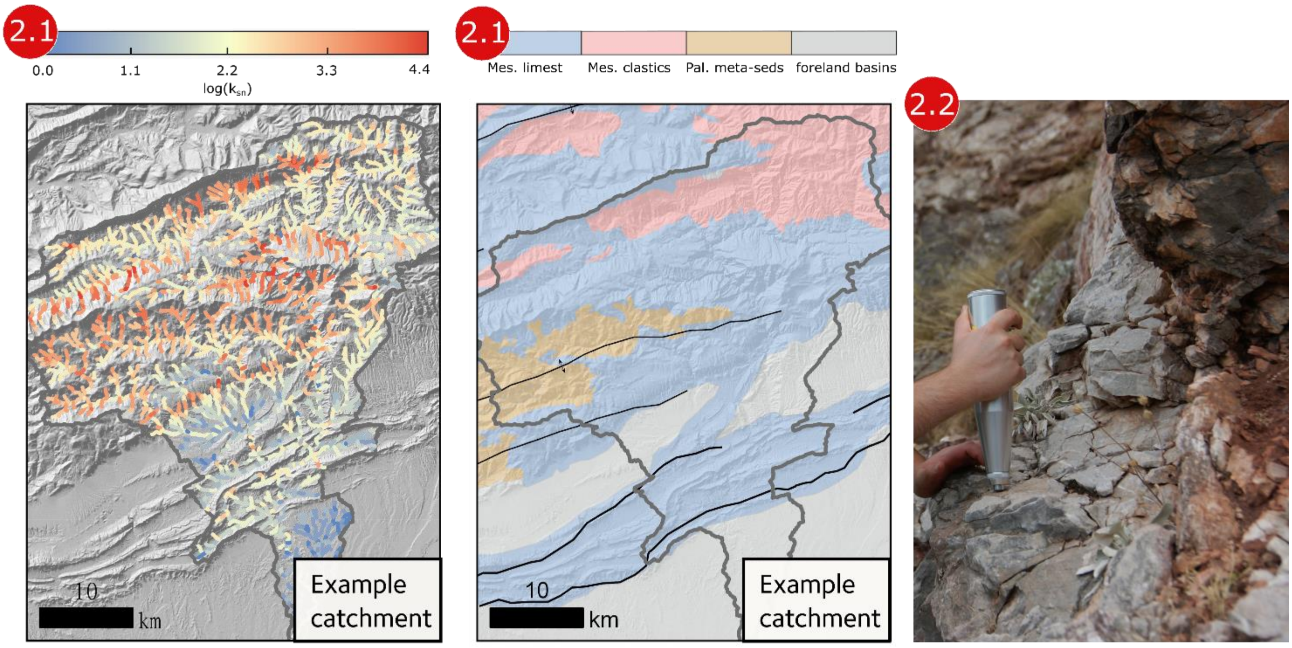

Figure 1. Relation between between topography, lithology and k_{sn} in a catchment example (method 2.1). Left panel is a map of k_{sn} for the Mgoun catchment on top of shaded topographic relief. The right panel corresponds to the same area but with the lithology represented in colors. Black lines correspond to main faults, and a black line with arrows indicates a synclinal axis. The right panel (method 2.2) demonstrates the use of a Schmidt Hammer, which is a spring-loaded hammer that reads a rebound value to estimate uniaxial compressive strength.

bedding, and secondary fabrics such as fractures and faults (Zondervan et al. 2020). All rock types include fractures, although the most pervasive fractures are found in the Palaeozoic meta-sediments which are highly deformed by mountain building. Fracure spacing, conmtinuity and orientation are affected by lithology, where mudstones have a higher density of fracturing then granites or limestones.

We quantify the effect of fractures and other discontinuities on erodibility by:

(i) collecting mechanical measurements of intact rock strength in the field (Figure 1); and

(ii) extracting the normalised river channel steepness of rock units from a digital elevation model (Figure 1).

Subsequently, we use this data to derive two different measures of rock erodibility: one of which includes the effect of discontinuities, and another one which excludes the effect of discontinuities.

2.1. Measure including the effect of discontinuities (k_{sn})

We derive the normalised river channel steepness index (k_{sn}) from a digital elevation model (DEM) as a measure of the river's stream power. We record the k_{sn} for each lithology using a geological map.

$$K \propto \frac{1}{{k_{sn}}^{n}} \qquad \text{(Eq. 2)}$$

where, *K* is the erodibility of the bedrock, and *n* is a constant in the stream power equation (see Zondervan et al. 2020 for a more detailed derivation of this relationship).

2.2. Measure excluding the effect of discontinuities (UCS)

We record the compressive strength of lithologies using a Schmidt hammer in the field as another measure of fluvial erodibility:

$$K \propto \frac{1}{UCS^2} \qquad \text{(Eq. 3)}$$

where, *K* is the erodibility of the bedrock, and *UCS* is uniaxial compressive strength (see Zondervan et al. 2020 for a more detailed derivation of this relationship).

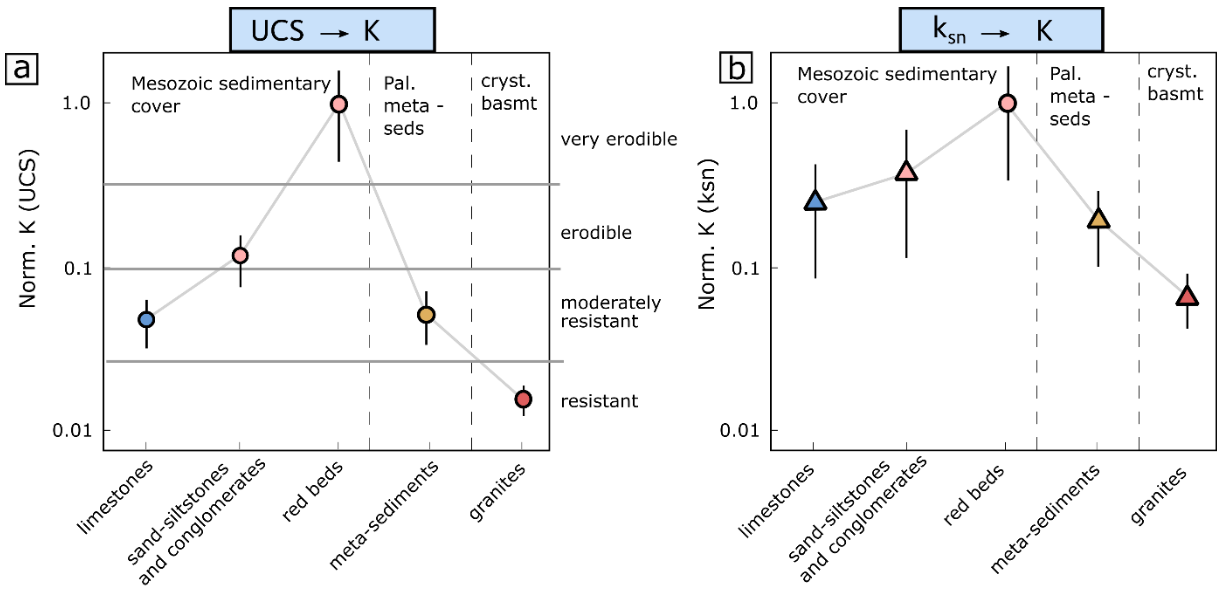

Figure 2. Fluvial erodibility K for each lithologic unit normalized against the weakest lithology derived from relative UCS values (a) and relative k_{sn} values (b). The range of erodibilities is highest in the least deformed, least fractured Mesozoic cover package, whereas similar units in the tectonically deformed and metamorphosed section of the mountain range have much a much smaller range of erodibilities. The range of erodibilities expressed in the landscape is one order of magnitude lower than expected from intact rock strength, constraining the role of fractures to reducing erodibility by no more than 50%.

3. Results and Conclusions

Calculated through intact rock UCS measurements, erodibility (K) is expected to vary by two orders of magnitude (Fig. 2a), whereas the topographic metric k_{sn} expresses only one order of magnitude variation in *K* (Fig. 2b).

Consequently, we estimate that fractures and other discontinuities effectively reduce the range of erodibilities between lithological units by up to 50%. In addition, across the mountain range we show that the tectonic history of more heavily deformed and metamorphosed sedimentary units reduced the range of erodibilities between lithologies (Fig. 2) through the development of fractures. Nonetheless, these units are still more resistant to erosion than most of the less deformed units in the Mesozoic cover.

Importantly, the role of fractures in reducing the control of lithology on erodibilities is limited to 50%, leaving an important role for lithology in landscape development even when fractures and discontinuities are present. There are other effects that could influence the difference between UCS and k_{sn}-derived erodibilities. Whilst the stream power model of bedrock river erosion only accounts for changes in river channel slope, field studies show that rock strength correlates with channel width (Allen et al. 2013), as well as valley width (Schanz & Montgomery 2016) and can influence the efficiency of river bed load in eroding underlying bedrock (Brocard & van der Beek 2006). Furthermore, there can be a dampening of k_{sn} value variations across lithological boundaries as sections of river with weak bedrock downstream of river reaches with hard bedrock can be armoured with blocks (e.g. Thaler & Covington 2016). Consequently, our constraints demonstrate that the role of rock strength in driving the evolution of landscapes and topography should not be discounted or underestimated, even when considering the role of fractures in erosion processes.

4. Acknowledgements

We thank Hugh Sinclair and Adam Forte for reviews on a version of this work published in Earth and Planetary Science Letters. Fieldwork to validate topographic analysis and take Schmidt hammer measurements during J.R.Z.'s PhD was supported by a University of Plymouth PhD studentship and the Geological Remote Sensing Group Student Award.

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