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Rock erodibility and the interpretation of low-temperature thermochronologic data

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ABSTRACT

Rocks vary significantly in strength and erodibility. Here we evaluate if rock erodibility variations should be considered when interpreting thermochronologic datasets. We do this by applying 1D thermo-kinematic numerical models that exhume two lithologies of contrasting erodibility. For thick layers (>2 km), soft over hard layering causes earlier cooling and therefore older thermochronologic dates than no layering, with the opposite true for hard over soft layering. In some circumstances, even 2–10x erodibility contrasts substantially influence the results, and a 10x erodibility contrast can be nearly as important as contrasts several orders of magnitude greater. Thinner alternating layers (<0.5 km) dramatically reduce the effect. The results imply that rock erodibility variations should not substantially influence thermochronologic data from most continental sedimentary packages, which are dominated by lithologic layering <0.5 km-thick. However, the effect may be important for data from basement samples exhumed beneath softer sedimentary rocks. For example, the abrupt cooling and erosion rate decrease recorded by thermochronologic data from Rocky Mountain basement uplifts of the western U.S. coincides with when erosion-resistant Precambrian basement was exposed after removal of softer sedimentary cover. These data may largely record a change in exposed rock type erodibility rather than a dramatic change in external erosional forcing. Our results suggest that in some cases, variations in rock erodibility should be considered when interpreting cooling and erosion histories from thermochronologic datasets.

1. Introduction

Low-temperature thermochronologic datasets are the primary means for estimating the timing, magnitude, and rates of erosion over extended (>1 Myr) timescales. Typically, abrupt shifts in cooling rates recorded by thermochronologic data are interpreted as changes in erosion rates caused by shifts in external erosional drivers, such as changes in rock uplift rate, base level, drainage patterns, or climate (e.g., Valla et al., 2011; Braun et al., 2012; Lease and Ehlers, 2013). However, it has long been qualitatively appreciated that variable rock hardness and erodibility can influence landscape evolution (e.g., Gilbert, 1877; Hack, 1960). This recognition raises the question of whether intrinsic differences in erodibility within a stratigraphic column can substantially alter erosion rates and affect thermochronologic data without changes in external erosional forcing. Here, "erodibility" is defined only as a function of the bedrock, rather than as a function of both climate and lithology as in geomorphic stream power models. The potential influence of erodibility is mentioned in a few thermochronologic studies (e.g., Glotzbach et al., 2011), but is not generally considered when interpreting such datasets.

Rock erodibility differences are a consequence not only of rock strength (Fig. 1A; e.g., Sklar and Dietrich, 2001; Lamb et al., 2015), but also of the density and orientation of fractures and bedding (e.g., Whipple et al., 2000; Dühnforth et al., 2010; Goode and Wohl, 2010; Marshall and Roering, 2014; Oskin et al., 2014; Forte et al., 2016). Rock strength effects may cause erosion rates to vary by as much as 4–5 orders of magnitude between soft rocks like shales to highly resistant lithologies like granites (e.g., Stock and Montgomery, 1999; Sklar and Dietrich, 2001; Bursztyn et al., 2015; Yanites et al., 2017), although weaknesses such as fractures may reduce these differences to less-extreme values. Modern denudation rates derived from cosmogenic nuclides and sediment supply information indicate that erosion rates can vary as much as 100-fold between drainage basins dominated by different rock types (e.g., Mueller and Pitlick, 2013). Together the data imply that lithology should be an important control on how landscapes change through time and on the thermochronometer record of erosion histories.

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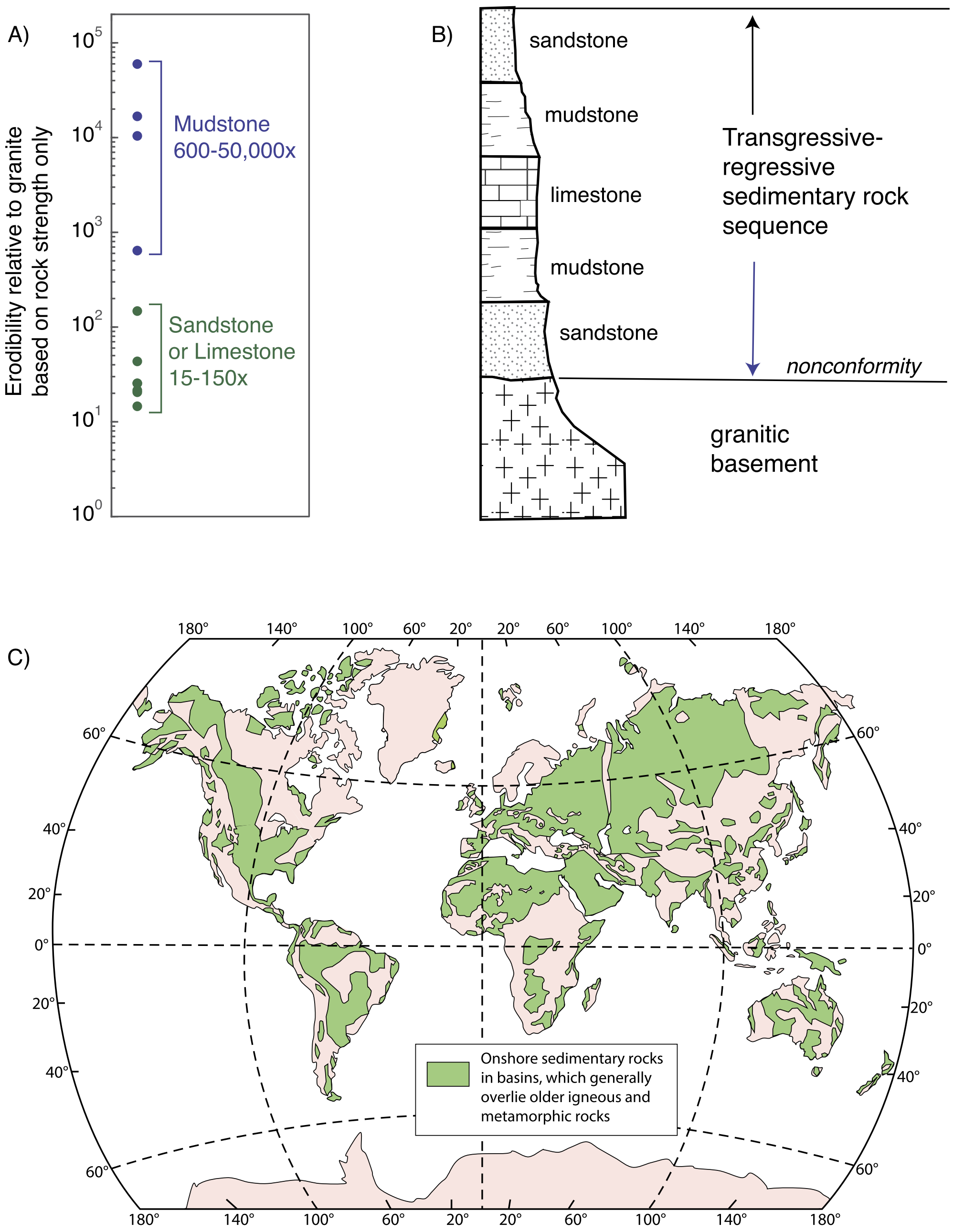

Fig. 1. A) Range of estimated erodibilities for shale, sandstone, and limestone relative to granite based on rock abrasion experiments of Sklar and Dietrich (2001). These relative erodibilities are based on inherent rock strength only, and do not include other effects such as the concentrations and orientations of fractures and bedding. B) Typical transgressive–regressive sedimentary rock sequence nonconformably overlying basement to illustrate common geologic circumstance of rocks with strongly contrasting erodibilities. C) Approximate distribution of major onshore sedimentary basins around the globe, nearly all of which sit on older crystalline basement rock. Intended to show the common circumstance of rocks that are generally softer (sedimentary rocks) overlying rocks that are generally harder (igneous and metamorphic basement rocks).

Geologic settings with rocks of contrasting erodibilities are the norm rather than the exception. For example, the classic transgressive–regressive sedimentary sequences of passive margins and foreland basins consist of alternating sandstone–mudstone–limestone packages (Fig. 1B), where the mudstones are more erodible than the sandstones and limestones (Fig. 1A, Sklar and Dietrich, 2001). These sedimentary sections reside in nonconformable contact with underlying igneous and metamorphic basement rocks that generally are more erosion-resistant than the sedimentary units (Fig. 1B). These rock sequences occur in diverse tectonic settings (Fig. 1C), from relatively stable cratons (e.g., Phanerozoic sedimentary sequences across the North American interior) to areas of intra-continental deformation (e.g., Rocky Mountain basement uplifts of the western U.S. Cordillera) to active orogens (e.g., Andean fold and thrust belt). Similarly, intrusive or fault contacts between harder igneous rocks and softer sedimentary strata will show this same abrupt rock erodibility variation. If intrinsic differences in erodibility within the rock column can strongly modify erosion rates in these settings without changes in external forcing factors, then this would have important implications for thermochronologic data interpretation.

Below we first quantitatively investigate the general problem by using simple 1D thermo–kinematic erosion models of two lithologies of contrasting hardness to explore the effects of layer ordering, erodibility contrast, background erosion rate, alternating layer thickness, and cumulative erosion magnitude on thermal histories and thermochronologic results. We focus the discussion on the probable effects of lithologic variability in common geologic set-