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Pliocene river capture and incision of the northern Altiplano: Machu Picchu, Peru

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Abstract: The Abancay Deflection, forming the northern edge of the Altiplano in the Peruvian Andes, is a remarkable geomorphological feature marking the along-strike segmentation of the Andes. Little is known about the timing and spatial distribution of exhumation in this area. To constrain the exhumation history of the Abancay Deflection and its drivers, we present apatite (U–Th)/He and fission-track thermochronology data from samples collected along an elevation transect at Machu Picchu. Geomorphological analysis demonstrates recent and continuing drainage reorganization recorded by the spatial distribution of the normalized steepness index (k_{sn}) and normalized integrated drainage area (χ) parameters. Thermochronologically derived cooling rates are converted into exhumation using regionally constrained geothermal gradients between 16 and 26°C km^{-1}. Time–temperature inversions imply steady and slow exhumation (<0.05 km Ma^{-1}) between 20 and 4 Ma, followed by rapid exhumation (>0.9 km Ma^{-1}) since 4 Ma. The timing of rapid exhumation, combined with the geomorphological analysis, suggests that fluvial capture of the previously endorheic Altiplano by the Urubamba River drove recent incision and exhumation. Depending on the value of the geothermal gradient used, total exhumation since 4 Ma can be explained by river incision alone or requires additional exhumation driven by tectonics, possibly associated with movement on the Apurimac fault.

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The Central Andes contain the second-highest and -widest plateau on Earth: the Altiplano. Topographic building-up of the Andes has occurred since at least the Cretaceous (*c.* 120–110 Ma; Jaillard and Soler 1996); the northern Altiplano acquired its modern elevation during the Miocene (Barnes and Ehlers 2009; Garzione *et al.* 2017; Schildgen and Hoke 2018). Tectonic, climatic and erosional interactions affecting the Altiplano and its eastward border, the Eastern Cordillera (Fig. 1), have been extensively studied in the southern Central Andes of Bolivia and Argentina (e.g. Strecker *et al.* 2007). Pliocene canyon incision, potentially induced by global climate cooling, has been inferred for the Eastern Cordillera in southernmost Peru (Lease and Ehlers 2013). In contrast, the evolution of the northern edge of the Altiplano and the Eastern Cordillera further north in Peru remains poorly documented. This area is formed by the Abancay Deflection (Fig. 1; Dalmayrac *et al.* 1980), a major Andean transition zone that separates the wide Bolivian orocline (Central Andes) to the south from the narrower Northern Andes to the north. The Abancay Deflection has higher (*c.* 0.3 km) average elevation and is much more incised than the low-relief and internally drained Altiplano to the south (Fig. 1c). Palaeoaltimetry data (Picard *et al.* 2008; Sundell *et al.* 2019) and biodiversity records (Hoorn *et al.* 2010) suggest that the study area acquired its modern elevation of *c.* 4 km before 5 Ma. At the scale of the Central Andes, different potential uplift mechanisms have been proposed, including crustal shortening (Barnes and Ehlers 2009), lithospheric delamination (Garzione *et al.* 2006) and crustal flow (Husson and Sempere 2003; for a review see Garzione *et al.* 2017). Tectonic shortening was transferred from the Altiplano to the Subandes of central Peru during the mid- to late Miocene (Horton 2005; McQuarrie *et al.* 2005; Espurt *et al.* 2011). The lack of structural, geomorphological and thermochronological data from the Eastern Cordillera, with only a few previous studies distributed around our study area (Fig. 1), however, renders the mode and timing of deformation transfer unclear (Gautheron *et al.* 2013). The mechanisms driving exhumation and surface uplift in the Abancay Deflection also remain enigmatic. The Machu Picchu Batholith, in the core of the Abancay Deflection, has been deeply incised by the Urubamba River and appears as a prime location to investigate the exhumation history of the Abancay Deflection and its drivers (Fig. 1). Here we present new apatite (U–Th)/He (AHe) and apatite fission-track (AFT) dates from the Machu Picchu Batholith. We use age–elevation relationships (AER; e.g. Fitzgerald and Malusà 2019) and inverse time–temperature modelling (QTQt; Gallagher 2012) to unravel the cooling and exhumation history of the core of the Abancay Deflection. As exhumation is generally driven by surface erosion, investigating the geomorphological evolution of an area is crucial to assess potential exhumation drivers. We couple the exhumation history to landscape evolution by extracting normalized steepness (k_{sn}) and the χ indices (Kirby and Whipple 2012; Perron and Royden 2013; Willett *et al.* 2014; Whipple *et al.* 2017) for the Urubamba drainage basin. These indices allow identification of slope anomalies (knickpoints) in the river profile and reorganization patterns between drainage basins, respectively. We combine these data to discuss potential mechanisms of Miocene to present exhumation in the Abancay Deflection.