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Styles and rates of long-term denudation in carbonate terrains under a Mediterranean to hyper-arid climatic gradient

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ABSTRACT

Carbonate minerals, unlike silicates, have the potential to dissolve almost completely and with high efficiency. Thus, in carbonate terrains denudation rate and style (the governing process of denudation, mechanical or chemical) should be more sensitive to climatic forcing. Using ^{36}Cl measurements in 39 carbonate bedrock and sediment samples, we calculate long-term denudation rates across a sharp climatic gradient from Mediterranean to hyper-arid conditions. Our samples were collected along the Arugot watershed, which drains the eastern flank of the Judea Range (central Israel) to the Dead Sea and is characterized by a pronounced rain shadow. Denudation rates of flat-lying bedrock outcrops sampled along interfluves differ by an order of magnitude from ~20 mm ka^{-1} in the Mediterranean zone to 1–3 mm ka^{-1} in the hyper-arid zone. These rates are strongly correlated with precipitation, and thus reflect the importance of carbonate mineral dissolution in the overall denudation process. In contrast, denudation rates of steep bedrock surfaces depend on the hillslope gradient, but only in the hyper-arid climate zone, indicating that mechanical processes dominate the overall hillslope denudation within this zone. The dominance of slope-dependent mechanical erosion in the hyper-arid zone is also reflected by an increase in spatially-average denudation rates from 17–19 mm ka^{-1} in the Mediterranean–semi-arid zones to 21–25 mm ka^{-1} in the hyper-arid zone. These higher rates are attributed to clast contribution from steep slopes under arid climate. This suggests an increased importance of mechanical processes to the overall denudation in the hyper-arid zone.

We demonstrate that the transition between chemically-dominated denudation to mechanically-dominated denudation occurs between 100 and 200 mm of mean annual precipitation. Long-term denudation rates across the Judea Range indicate that between Mediterranean and hyper-arid climates, chemical weathering rates are limited by precipitation. Nevertheless, in more humid climates, chemical weathering rates are apparently limited by the rates of carbonate mineral dissolution. This study demonstrates that carbonate terrains have the capacity to shift between mechanically and chemically dominated denudation in response to changes in precipitation. Similar transitions in response to changes in temperature or the level of tectonic activity have been previously reported. We suggest that the abrupt nature of such transitions can be primarily attributed to the efficiency of carbonate dissolution processes and the competition between surface and subsurface drainage systems in carbonate terrains.

1. Introduction

Denudation, the lowering of Earth's surface, occurs through the combined action of mechanical erosion and chemical weathering. The style and rate of denudation (i.e. governing erosive process, mechanical or chemical) reflect complex relationships between tectonic activity, climate, and surface processes. These relationships determine the correlation between denudation rate and topographic, tectonic, and climatic variables. In mountainous silicate terrains, climatic variables such as mean annual temperature or precipitation typically show weak correlations with denudation rates (Portenga and Bierman, 2011; Riebe et al., 2001; Summerfield and Hulton, 1994; von Blanckenburg, 2005), while hillslope gradient and rates of tectonic uplift typically show strong correlations with denudation rates (Ahnert, 1970; Granger et al., 1996; Matmon et al., 2003; Milliman and Syvitski, 1992; Montgomery and Brandon, 2002; Riebe et al., 2001). Such dependencies indicate

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that mechanical erosion processes control the overall denudation of mountainous silicate terrains. Riebe et al. (2004) identified a linear and positive correlation between chemical weathering and total denudation rates and attributed this dependency to the limitation of chemical weathering reactions by the supply of new rock surfaces through mechanical processes (or 'supply-limited' chemical weathering). This correlation may reverse where mechanical weathering processes intensify to a level in which denudation rates become limited by the kinetics of mineral weathering and the residence time of rock clasts in the weathering zone ('kinetic-limited' chemical weathering) (Blum and Erel, 1997; Dixon et al., 2012; Gabet and Mudd, 2009; West et al., 2005).

Carbonate terrains may respond differently to climatic or tectonic forcing because carbonate minerals dissolve almost completely and with high efficiency (Ford and Williams, 2007; Gabrovšek, 2009). In carbonate terrains, remnants of mechanical erosion reside where dissolution was insufficient to fully remove them. In glaciated and dry climates, where the carbonate solutional potential is low, mechanical erosion products accumulate in moraines (Woodward and Hughes, 2011), and alluvial and colluvial deposits (Pope and Wilkinson, 2005, and references therein) in a similar manner to silicate terrains. Mass wasting and accumulation of clastic sediment bodies also occur where rates of channel incision and tectonic uplift exceed the rate of chemical processes (Ryb et al., 2013). In carbonate terrains, most chemical weathering occurs when carbonate minerals react with carbonic acid produced as CO_2 dissolves in water. Rates of chemical weathering are therefore limited by reactant availability (H_2O, CO_2, or $MeCO_3$, where Me is a metallic cation, usually Ca or a Ca–Mg combination) or by the acidified water residence time. Hence, chemical weathering efficiency is a complicated process that depends on precipitation, temperature, soil and vegetation cover, flow hydrodynamics, and bedrock composition (Atkinson and Smith, 1976; Buhmann and Dreybrodt, 1985; Szramek et al., 2007; White, 1988). Nevertheless, assuming an open system, with constant pCO_2 and sufficiently long runoff residence time, chemical weathering rates are expected to increase linearly with precipitation (Bluth and Kump, 1994; White, 1984).

Chemical weathering rates have previously been calculated in carbonate terrains by an integration of solute load measurements in a drainage basin over annual to decadal timescales (Bluth and Kump, 1994; Gabrovšek, 2009). Recent studies applied cosmogenic ^{36}Cl measurements in bedrock and sediments to quantify denudation rates over 10^3–10^5 year timescales (Haviv, 2007; Matsushi et al., 2010a, 2010b; Ryb et al., 2014; Xu et al., 2013).

Here, we utilize cosmogenic ^{36}Cl to obtain denudation rates across central Israel, over a Mediterranean to hyper-arid climatic gradient, in order to investigate the impact of topographic and climatic variables on denudation rate and style. We analyze both carbonate bedrock samples and sediment samples that average denudation rates on local and basin-wide scales, respectively (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). We show that denudation rates correlate with hillslope gradient under hyper-arid conditions where mechanical erosion processes are dominant. Conversely, where chemical weathering processes are dominant, we show that denudation rates correlate with mean annual precipitation. As climate becomes drier, we show that carbonate dissolution capacity decreases and the relative contribution of mechanical erosion processes to the overall denudation increases. Comparing our results with published long-term denudation rates from more humid climates suggests that as precipitation increases, chemical weathering becomes limited by carbonate minerals dissolution kinetics. Finally, we present a conceptual model that explains how tectonic activity, precipitation and temperature compete to control the style of denudation in carbonate terrains.

1.1. Study area

The mountainous interior of Israel rises up to ∼1000 m above mean sea level between the Mediterranean and the Dead Sea Rift basins (Fig. 1). Our study focuses on the central Judea Range (Fig. 1). This range is mostly composed of Albian–Turonian marine carbonate rocks (dolomite, limestone, and marl), flanked by Senonian units (mostly chalk, chert, and marl) (Bentor et al., 1965). The topography of the range follows a fold structure that is composed of several short wavelength (10–20 km) asymmetrical folds. These folds are superimposed on a longer wavelength (∼70 km) structural arch that developed in response to the subsidence of the Dead Sea Rift (Wdowinski and Zilberman, 1996, 1997) since the late Miocene. Prominent knickzones along stream profiles are located upstream from the western Dead Sea Rift escarpment. These have been attributed to the retreat of a series of waterfalls from the escarpment since its formation (Haviv et al., 2006; Steinitz and Bartov, 1991) (Fig. 1). Pleistocene uplift of the entire Judea Range is generally attributed to the structural arching of the western margin of the Dead Sea Rift (Begin and Zilberman, 1997). Ryb et al. (2013) demonstrated that an early-to-mid Pleistocene uplift of ∼100 m was followed by tectonic quiescence over the western flank of the Judea Range. During the time of tectonic stability from mid-Pleistocene to the present, hillslope and interfluve denudation rates (21 ± 7 mm ka^{-1}), kept pace with base level lowering (Ryb et al., 2014). On the eastern flank of the Judea Range, a similar incision rate (22 ± 2 mm ka^{-1}) was calculated upstream of a knickzone in the David watershed above the Dead Sea Rift escarpment (Fig. 1) (Haviv, 2007). This similarity in incision rates along both flanks of the Judea Range (excluding incision below the knickzones of the Dead Sea escarpment) supports the hypothesis that tectonic uplift of the entire range has been relatively homogeneous during the time scales over which denudation rates are averaged, and suggests that variations in denudation rate and style reflect the climatic gradient in the study area.

The western flank of the range faces the predominate winds that carry humidity from the Mediterranean Sea and sustains a sub-humid Mediterranean climate. The eastern flank is in a rain shadow and sustains a climatic gradient from Mediterranean conditions (mean annual precipitation (MAP) 500–700 mm) at the water-divide to hyper-arid conditions (MAP $<$ 100 mm) near the Dead Sea escarpment (Fig. 1). Rainfall is generally limited to the winter (December to March) while summers are dry. The present precipitation gradient probably persisted throughout Pleistocene glacial–interglacial cycles since the primary moisture source (Mediterranean Sea) did not change during this time (Bar-Matthews, 2014; Enzel et al., 2008; Kolodny et al., 2005).

This study focuses on the Arugot watershed situated on the eastern flank of the central part of the Judea Range (Fig. 1). About 30 km separate the upper reaches from the base level. Over this distance the elevation drops by ∼1400 m, 550 m of which occurs through a sequence of waterfalls at the lowest 5 km of the main channel. The Arugot watershed exhibits a dramatic precipitation gradient between the upper (Mediterranean) and lower (hyper-arid) reaches, and is therefore ideal for our purpose (Fig. 1). In the Mediterranean zone of the watershed, soil (terra rossa) is mostly concentrated in pockets between patches of exposed bedrock and the vegetation cover consists of low Mediterranean shrubs. Eastward from the Mediterranean zone, as climate becomes increasingly arid, the hillslope vegetation cover gradually disappears, soil pockets are absent, and rock debris, which occasionally forms talus aprons at the base of slopes, becomes more abundant (see online data repository item DR1). Upstream from the waterfalls, hillslopes are dominated by exposed bedrock. Consequently, hillslope erosion is considered to be detachment-limited throughout the study area.