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Mean bedrock-to-saprolite conversion and erosion rates during mountain growth and decline

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ABSTRACT

Weathering and associated atmospheric CO_2 consumption are thought to increase during the erosion of uplifting mountain ranges, but the effect of enhanced erosion on weathering is still the subject of active debate. We explore the possibility that erosion heterogeneity in uplifting landscapes significantly impacts the temporal relationships among mean uplift, erosion and weathering using a 3D landscape evolution model applied to a synthetic surface with different uplift and climate scenarios. Although we do not strictly simulate the weathering outflux of the mountain, we analyze the weathering response through the evolution of the mountain-mean saprolite production rate and compare it to the mountain-mean erosion rate through time. The parametrical analysis shows that the temporal relationship between the mean erosion and saprolite production rates depends mainly on the ratio of the maximum saprolite production rate and the uplift rate w_m/U. We explore two end-members. (1) When $w_m/U > 1$, which corresponds to mountain ranges under a hot and humid climate, the mean erosion and saprolite production rates vary at the same rate during the uplift and after, once the uplift is stopped. When the uplift is stopped, the mean saprolite production increases and then decreases locally at different times. This heterogeneity induces an overall decrease in the mean saprolite production rate. (2) When $w_m/U < 1$, which corresponds to most of the mountain ranges at mid-latitudes, the mean saprolite production rate peaks early and then remains constant, while erosion continues to increase and reaches a steady-state after a time corresponding to ~3–5 times the time needed to reach the mean saprolite rate peak. When the uplift is stopped, both the erosion and saprolite production rates decrease, although at different rates with time lags of million years in model time. These results illustrate that a causal relationship between erosion and saprolite production can lead to asynchronous evolutions of their mean values at the mountain range scale. Furthermore, the model suggests that the weathering of large flat continental surfaces should be considered in the geological carbon budget as their size may compensate for their low weathering rate.

1. Introduction

The weathering of continental silicate minerals consumes atmospheric CO_2 and hence modulates the global climate over millions of years (Walker et al., 1981). Weathering is a complex process, potentially controlled by many parameters, including runoff (White and Blum, 1995; Oliva et al., 2003), surficial temperature (Brady, 1991), vegetation (Moulton et al., 2000; Roelandt et al., 2010), lithology (Dessert et al., 2003), and mechanical erosion (West et al., 2005). Since the early 1990s, there has been an intense debate about the potential role of uplifted terranes (called mountains in the following) on silicate weathering and long-term climatic evolution. It has been suggested that mountain uplift promotes silicate weathering by breaking rocks, and hence by increasing the reactive surface of the rocks undergoing chemical dissolution (Raymo et al., 1988; Raymo and Ruddiman, 1992). This hypothesis, supported by the presence of huge accumulations of sediments at the foot of active mountain ranges, led several authors to suggest that mountain uplift, through its erosion and subsequent accelerated consumption of atmospheric carbon, is the major controlling factor of global climate over geological times (e.g. Raymo and Ruddiman, 1992). This link between mountain uplift and climate change has been particularly stressed for the Cenozoic, during which the long-term global cooling starting around 40 Ma is often attributed to the Himalayan uplift.

Alternatively, several authors have suggested that large mountain ranges, such as the Himalayas, store CO_2 as buried organic carbon in fan sediments, due to the high sedimentation rate promoted by intense erosion (France-Lanord and Derry, 1997; Galy et al., 2007). They point out that this process might be up to five times more efficient than the consumption of atmospheric carbon through silicate weathering.

Adding further uncertainties to the role of mountain ranges in the global carbon cycle, a recent work suggests constant global weathering fluxes during the last 12 Ma, despite the uplift of the major Cenozoic mountain ranges (Willenbring and von Blanckenburg, 2010). These constant global weathering rates fit with the stable atmospheric CO_2 level estimated from the carbon isotopic fractionation of the marine biosphere (Pagani et al., 2005). The authors concluded that mountains are

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not a key factor in the late Cenozoic climatic history. However, because of the relatively short record period (12 million years), this synthesis might have missed some key steps in the weathering history of large Cenozoic mountain ranges (Goddéris, 2010). For instance, a monsoon intensification impacting the weathering rates occurred 20 million years ago in the Himalayas (Guo et al., 2002), i.e. 8 million years before the beginning of the weathering rate reconstruction by Willenbring and Von Blanckenburg (2010).

The role of mountain ranges in climate evolution is thus still debated and far from being solved. The possible link between mountain rise, rock weathering and climate evolution is supported by the existence of a correlation between riverine dissolved load and suspended load. This correlation is shown in some cases (Gaillardet et al., 1999; Millot et al., 2002; Jacobson and Blum, 2003; Riebe et al., 2004; West et al., 2005; Hren et al., 2007; Dixon et al., 2012). In other cases, the correlation is weaker or even missing and the differences in the weathering fluxes from one site to another are best explained by runoff and temperature variations (White and Blum, 1995; Oliva et al., 2003; West et al., 2005).

1D models of the chemical evolution of minerals in a soil column were developed to explore the coupling between weathering and surface erosion (see review in Brantley and Lebedeva, 2011). These models have provided some useful insights into the behaviors of weathering and erosion fluxes. They predict that low erosion rates allow thick saprolite to develop. The thicker the weathered layer, the smaller the weathering outflux. In this case, an increase in the erosion rate decreases the saprolite thickness and increases the weathering outflux (Ferrier and Kirchner, 2008; Gabet and Mudd, 2009). This regime has been called “supply limitation”, in order to indicate that the weathering flux is controlled by the rate at which the parent rock is converted into saprolite. However, when the erosion rate rises above a given threshold, the residence time of the fresh minerals in the weathered layer becomes too short and the weathering outflux decreases (Ferrier and Kirchner, 2008; Gabet and Mudd, 2010). In this case, the weathering rate of these minerals depends mainly on the local temperature and runoff, which control the kinetics of the chemical reactions. This regime has been defined as “kinetic limitation”. Under this regime, weathering fluxes are predicted to decrease when the erosion rate increases (Gabet and Mudd, 2009; Lebedeva et al., 2010; Dixon et al., 2012). Dixon et al. (2012) documented a decrease of this type in the San Gabriel Mountains of California.

These two regimes and the existence of an optimum erosion rate for which the weathering outflux is maximum have been suggested by many 1D models (Waldbauer and Chamberlain, 2005; Hren et al., 2007; Ferrier and Kirchner, 2008; Gabet and Mudd, 2009; Hilley et al., 2010; Lebedeva et al., 2010). By extrapolating these 1D model results to the continental scale, it has been predicted that during the early stages of mountain uplift, small erosion rates effectively increase the weathering outflux, but then the weathering flux should stabilize (West, 2012) or even decrease when the erosion rate becomes too large (Hren et al., 2007; Gabet and Mudd, 2009; Hilley et al., 2010). Such behavior contradicts the hypothesis that mountain uplift and the associated weathering constitute a significant carbon sink (e.g. Dixon et al., 2012).

Nevertheless, the evolution of weathering and erosion averaged over a mountain range may differ from that of a soil column (Anderson et al., 2012). 3D landscape evolution models predict that the sediment outflux from a mountain range adapts to uplift or climate pulses with a time lag that can reach several thousands to millions of years (e.g. Kooi and Beaumont, 1994; Tucker and Slingerland, 1997; Whipple and Tucker, 1999; Davy and Crave, 2000; Densmore et al., 2004; Carretier et al., 2009). During this transient stage, the mechanical erosion rates change over time both locally and on average over the uplifted domain. Some portions of this domain may evolve under the “supply limitation” regime, while other parts work under the “kinetic limitation” regime. Recent 2D models show this type of behavior for a hillslope (Lebedeva and Brantley, 2013). How these differences are averaged over the uplifted domain and through time has however not been evaluated yet. Consequently, it remains difficult to predict the temporal variations in weathering and erosion outfluxes of mountain ranges. We hypothesize that a significant time shift between the mean erosion and mean weathering may arise from the averaging of heterogeneous erosion and weathering rates within a mountainous domain. We address the following questions: does the mean weathering rate of mountain ranges peak for some mean erosion rate, as suggested by 1D models? Is it possible that this peak occurs only at an early stage of mountain building? Is the weathering rate larger during mountain uplift or during mountain decline? Finally, which is the most efficient in terms of consuming atmospheric carbon for a given period of time: a large slowly eroding pediplain or a rapidly eroding mountain range of much smaller size?

In order to tackle these questions, a 3D modeling approach is required, where both erosion and weathering depend on climate, lithology and uplift. In this contribution, we use a landscape evolution model that couples mechanical erosion and saprolite production. The model does not incorporate the concentration evolution of the chemical elements. As such, it does not predict weathering fluxes. Weathering processes are lumped into saprolite production laws, so that the bedrock-to-saprolite conversion rate adapts dynamically to erosion and climate variations. We analyze the temporal evolution of the saprolite production rate and the erosion rate averaged over the area of a synthetic continental surface for different uplift and climatic boundary conditions. Then, we discuss the potential implications of the mean saprolite production rate for the weathering outflux of mountain ranges. We carry out this analysis for a three-step scenario during which a continental surface is kept near base level, then uplifted and finally declines.

2. Model setup

In the following, the saprolite is the in-situ weathered material from the bedrock, the soil is the uncohesive material deposited or moving above and the regolith is the layer composed of saprolite and soil.

2.1. Algorithm and erosion laws

The model used in this study is a landscape evolution model called CIDRE. CIDRE solves local mass balance between eroded and deposited material on square cells to predict topographic variations at different time steps (Carretier et al., 2009; Pepin et al., 2010). CIDRE uses a multiflow algorithm that allows water and sediment to flow toward different directions (“multiflow”) at the same time (Tucker and Hancock, 2010). The multiflow algorithm is useful to model sediment transport processes on gentle slopes (Carretier and Lucazeau, 2005; Pepin et al., 2010), which occurs in simulations presented here.

In the present simulations, the model takes into account two layers, the cohesive bedrock and the uncohesive material above, which erode differently. Uncohesive material includes in situ weathered layer (saprolite) and the sediment in transit above it (also called “soil” in some studies—e.g. Heimsath et al., 1997, Dixon et al., 2009a and b). It is assumed that weathering destroys the cohesion of bedrock (Dixon et al., 2009b). Saprolite clasts are thus considered as erodible as other clasts coming from upstream erosion and deposited on the cell. Doing this we follow Anderson and Humphrey (1989), Tucker and Slingerland (1994) and Strudley et al. (2006a). In practice, there is a difference in cohesion and clast size between saprolite and soil (e.g. Braun et al., 2012), and the erodability of the saprolite depends on its weathering extent (Dixon et al., 2009a). Considering a simple conversion from cohesive bedrock to uncohesive saprolite allows us to account for the critical role of saprolite weathering on erosion (Dixon et al., 2009b), but this simplification overestimates the saprolite erodability, which is an issue to be discussed in this paper.

A simulation starts with a digital elevation model composed of square cells. At the beginning of each time step (1 year), cells are sorted