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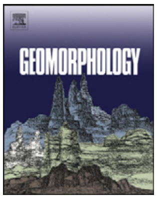

Climate and hillslope degradation vary in concert; 85 ka to present, eastern Sierra Nevada, CA, USA

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ABSTRACT

Degradation in the landscape results when the interactions of climate, substrate, and biota dislodge and transport sediment that is mantling landforms. Rates of degradation through time control landform stability and resiliency. Therefore, records of past degradation rates can be used to inform us on how a given landscape responded to significant changes in past climates. For example, climate has varied at many temporal scales, and some of the largest recent shifts enabled the glacial advances and retreats in time scales of 20–100 ka. Therefore, it is reasonable to expect that the rate of landscape degradation has also varied at similar time scales. However, the general hillslope diffusion equation that is commonly used to model cross-profiles of hillslopes on time scales of thousands to tens of thousands of years typically relies on a constant and optimized rate parameter to generate a model cross-profile approximating the current observed landform cross-profile. Using a time-varying diffusivity parameter, we generated three separate degradation scenarios for the Mono Basin moraine in the eastern Sierra Nevada, CA, USA, in order to assess the potential impact of varying past climates on sediment transport. We used published paleoclimate records in the study area and modern rates of surface degradation from climates that correspond broadly to those paleoclimates. The results indicate that, in this case, the climate driven and, therefore, time-dependent degradation model produces a good fit between the modeled and observed landform profiles. Results showed that, when the surface elevations of the reference case (constant optimized diffusivity) were compared through time to the surface elevations of the time-dependent model, the differences were relatively small. The largest deviation was found to occur during the Last Glacial Maximum (LGM). We found that for investigations into the geological effects of climate change in glacial and polar regions, the use of time-varying diffusivity offers improved estimates of landform degradation through time. The rates of surface lowering that change through time are important for analyses of the depths of past exposures, exposure dating, and renewal or preservation of surfaces, all of which are relevant in landscape dating, in interpretation of paleoecology, and in modeling landscape evolution.

1. Introduction

The interaction of climate, substrate and biota that result in landform degradation can be measured as topographic change over time. Degradation rates, as indication of the effect of past climates on erosion, can be used to model the topographic evolution of landforms in accord with past changes in climate. For this reason, model parameterization of landforms is critical for modeling landscape evolution. Models of landscape evolution need to be able to incorporate the general effects of climate which are exhibited by the transport of surface sediment and the density and variety of biota that result in the degradation of the land surface in order to generate physical process based models that can be tested against reality (Tucker and Hancock, 2010). Also, geologic investigations that use preserved surfaces to assess rates of change of chemical processes that occurred in the past within the uppermost meters need insight into how mobility of the surficial sediment has responded to processes that have varied through time.

Climate is one such known force to have varied through recent glacial advances and retreats. These climatic fluctuations are evidenced by sets of moraines, e.g. in the eastern Sierra Nevada, CA, USA. Such climate forcing attests that present landscapes are not products of the current climate but, rather, are the cumulative effects of climate changes in interaction with substrates over thousands to tens of thousands of years. Instead of being stable end products, landscapes are results of the resilient response of landforms to the combined forces that degrade them. Some responses may affect the floral assemblages that may leave variable amounts of bare earth which is then exposed to agents of erosion. For this reason, rates of past landform degradation are expected to vary in accord with past shifts in climate.

Changes in sediment transport rates as well as in vegetation, both of which often reflect corresponding changes in climate, have been recorded in proxy climate records from pollen and lake sediments. For example in the western USA, pollen records indicate changes in vegetation

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communities (Tausch et al., 1993; Woolfenden, 1996; Mensing, 2001; Minnich, 2007) and lake sediment cores show variable sedimentation rates (Benson et al., 1997; Smith and Bischoff, 1997; Bischoff and Cummins, 2001; Zimmerman et al., 2011; Street et al., 2012 Reheis et al., 2014). Such records provide relative and indirect measures of the effect of past climate on degradation of landform surfaces.

As fundamental landscape processes, hillslope erosion and sediment transport together provide a basis for quantifying the effects of climate on landscape evolution. However, the evidence for past climate forcing on the land surface has not been incorporated into approaches for hillslope modeling at the landform and glacial scales, and so the effects of past climates on hillslope erosion have not been quantified. Conventional analyses have assessed degradation of topographic gradients with a basic hillslope diffusion equation. When a hillslope diffusion equation is applied to a two-dimensional cross-profile of a hillslope, the results have been found to closely approximate field observations of cross-sections of sloping landforms such as glacial moraines, fault scarps, and wave-cut terraces (Hanks et al., 1984; Pierce and Colman, 1986; Anderson and Humphrey, 1989; Hallet and Putkonen, 1994). Modeling results also have been corroborated mathematically, showing that a time-averaged diffusivity coefficient does not differ significantly from the time-dependent parameter at a million year time scale (Skianis et al., 2008). Given the known shifts in climate occurring over the last glacial and interglacial cycle and published records of variability of degradation in association with current regional climates, we set out to test whether the effect of climate forcing on landform degradation could be quantified at a shorter, glacial–interglacial, time scale. Degradation modeling that includes the effects of past climates on the land surface at shorter time scales (10 s of ka) would provide a quantitative means of assessing the time scales of landform stability and thresholds for surface mobility.

Regions with a robust glacial record, such as the eastern Sierra Nevada, CA, USA, provide well dated targets with which to quantify the effects of past climates on landform degradation. The mobility of the till composing the substrate of moraines may be quantified as the surface flux transported across the landform surface. The mobility of the regolith, or unconsolidated sediment mantling these natural hillslopes, provides a target comparable with similar landforms on the basis of a transport rate and climatic region. Published glacial chronologies in the eastern Sierra Nevada indicate times of glacial advance in the region (Phillips et al., 1990, 1996; Gillespie and Zehfuss, 2004; Rood et al., 2011). Because glacial advances and retreats are controlled by combined effects of temperature and precipitation, conditions that accumulate or melt snow, such glacial chronologies provide temporal evidence for past climate variability in the region.

2. Study area

The alpine region of Sierra Nevada, CA, USA, a westward tilting fault block resulting from Miocene uplift of the late Jurassic Magmatic arc, is the geological setting for a landscape carved by Pleistocene glaciation (Gillespie et al., 1999; Moores et al., 1999). As glaciers, originating on the crests of the mountains, advanced down the valleys, eroded debris was deposited and formed lateral moraines on the flanks of the advancing glaciers. Lateral moraines are landforms recognized by their approximation of elongated ridges. Dating of other moraines in the broader region, extending from the Olympic Mountains in the northwestern USA to the Uinta Mountains along the Utah-Wyoming border (Thackray, 2008) and to the far southwestern margin of California in the San Bernardino Mountains (Owen et al., 2003), indicate variable responses by regional glaciers to the general global climate fluctuations (Licciardi et al., 2004; Thackray, 2008). Glacial advance and retreat through mountain valleys was driven by temperature and precipitation that not only drove glacial activity, but may also be assumed to have affected rates of hillslope degradation through sediment transport processes.

The Mono Basin moraine, one of many lateral moraines deposited in this region by late Pleistocene glaciers, is located in Sawmill Canyon, CA, USA (37.87°N; 119.14°W) and has a mean altitude of 2350 m asl and is located 8 km south of the town of Lee Vining and Mono Lake (Fig. 1). A younger adjacent Tahoe moraine in neighboring Bloody Canyon contributes to the complex of glacial deposits that indicate the variable extent of glacial activity during the glacial period in the late Pleistocene. Latest published ages based on cosmogenic isotope dating compiled by Gillespie and Zehfuss (2004) are between 80 and 60 ka for the Mono Basin moraine and 50–42 ka for the Tahoe moraine. Additional calibration parameters for ^{36}Cl cosmogenic isotopes for dating moraine boulders extends the possible upper age limit of the Mono Basin moraine to 85 ka.

Lying on the border of two major physiographic provinces — the Sierra Nevada and the Great Basin — Mono Basin is characterized by large seasonal and annual variability in precipitation. A majority of the precipitation occurs in winter in the form of snow. The variability in precipitation is attributed in part to the complex effect of the mountains on Pacific storms. The area became a closed basin about 3 Ma ago, when a combination of faulting of the eastern scarp of the Sierra Nevada and down warping of the north and south sides of the basin occurred (Mono Basin Ecosystem Study Committee, 1987). The current climate of the region is considered semi-arid. Mean annual precipitation for the 23-year record (1989–2012) according to NOAA (2014) is 351 mm ($\sigma = 163$ mm). Mean annual temperature for the same time range is 8.8 °C ($\sigma = 3.4$), as based on temperature records from NOAA

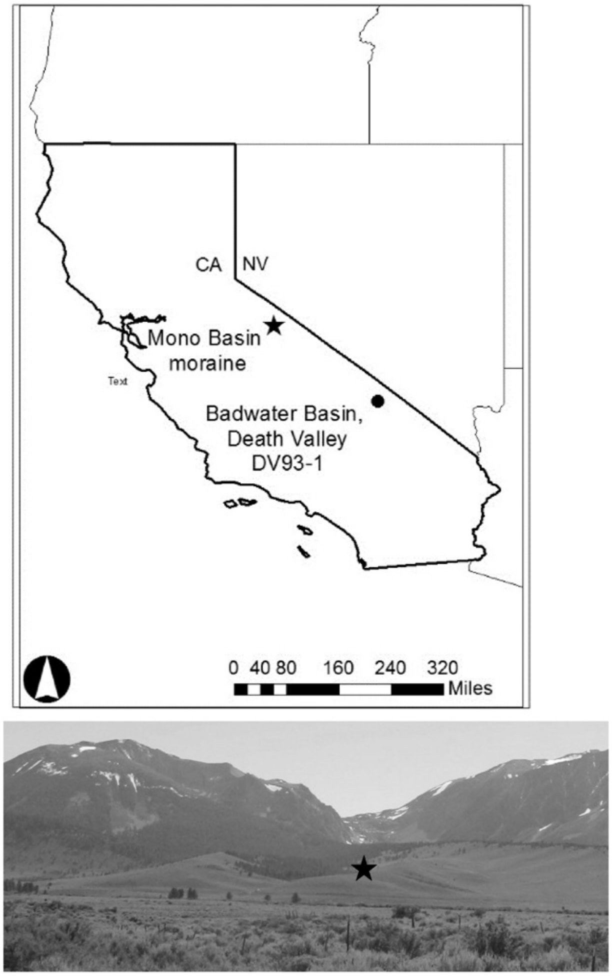

Fig. 1. Location map and photo of the Mono Basin moraine in eastern Sierra Nevada, CA, USA. Study site is labeled with a star. Map also shows the location of the DV 93-1 core site where halite fluid inclusions were sampled and used as temperature proxy record (Lowenstein et al., 1999) in the present study (see Section 3.2).