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Silt production as a function of climate and lithology under simulated comminution

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ABSTRACT

Production of the silt-sized particles composing loess represents a critical step in its ultimate formation, but the volume and rate of production in different settings remain underdetermined. This study addresses the influence of climate and source lithology on silt formation by subjecting natural alluvial/fluvial sand from systems characterized by varying climatic setting to simulated comminution. Bulk samples from comparable transport distances were collected from a hot-arid (California desert) alluvial system, hot-humid (Puerto Rico) fluvial system, and cold-humid (Norway) proglacial fluvial system, and sieved to isolate the coarse-very coarse sand fraction for experimental milling. Source rocks in all three systems consist of granitoids, with some contributions from foliated coarse-grained metamorphic rocks (gneissic and schistose) in Norway. Results indicate that contributions from coarse-grained foliated lithologies impart a negligible effect on rate of silt production from the sand starting material. Climatic setting imparts no significant difference on sand durability, but influences clay production at later stages of comminution for the Puerto Rico sample, presumably owing to the effects of deep chemical weathering prior to physical transport. Comminution and silt production in all experiments exhibit exponential decay wherein rapid initial rates diminish with time. This is interpreted to reflect the effects of the dynamic milling conditions (particle size and distribution, and slurry viscosity), as well as particle strength, with the latter including both relative strengths of different minerals in general, and the influences of lattice defects and microfractures in quartz in particular. Empirical observations reveal that silt fractions of the natural alluvial/fluvial samples, collected at comparable transport distances (5–7 km) in the respective systems, exhibit significant differences. Bulk sediment samples from the Norwegian proglacial system contain substantially more silt (3–10 times) than either of the other two localities, implying a significant difference in the natural processes operating to generate silt in these different field settings. We suggest this difference reflects the efficacy of glacial grinding in silt production.

1. Introduction

The production of silt-sized particles represents a critical step in the ultimate formation of deposits of eolian silt known as loess. A number of processes lead to production of silt-sized material (4–62.5 μm for geologists), but the volume and rate of production in different settings remains underdetermined. Loess is widely recognized as an excellent paleoclimate archive, and its finer (<10 μm dust) fraction additionally acts as an agent of climate change (e.g., Kukla et al., 1988; Porter and An, 1995; Mahowald et al., 2011). The loess of northern Serbia, for example, forms one of the thickest and most stratigraphically complete paleoclimate archives in Europe (Basarin et al., 2014). The spatial association of loess with formerly glaciated regions is generally attributed to the role of glacial grinding in producing voluminous fines in the silt mode (e.g., Smalley, 1966, 1990, 1995; Kuenen, 1969; Assallay et al., 1998; Muhs and Bettis, 2003), although the role of rivers in transporting and concentrating this material is also important (Smalley et al., 2009). Loess in Europe, for example, occurs primarily between the latitudes of ~40–60° in proximity to the margins and drainages of the former ice sheets (Muhs and Bettis, 2003; Haase et al., 2007). However, loess and "loess-like" sediments also occur in regions far removed from areas of Pleistocene glaciation, such as the peri-Saharan region (e.g., Yaalon, 1974; Coudé-Gassen, 1987; Muhs and Bettis, 2003; Crouvi et al., 2010), indicating that non-glacial processes formed the fines within these loess deposits. For

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example, fluvial and eolian saltation and abrasion, as well as salt-, frost- and insolation weathering can also play roles in silt production (e.g. Nahon and Trompette, 1982; Pye, 1987; Assallay et al., 1998; Wright, 2001; Muhs and Bettis, 2003; Crouvi et al., 2010, 2012).

Perhaps the best-recognized accumulation of loess on Earth today—the Chinese Loess Plateau—constitutes the most complete Quaternary succession of loess known. This succession houses a paleoclimatic record that includes the impacts of northern hemisphere glaciation and attendant monsoonal variation at this site extending to 2.8 Ma, with the subjacent Red Clay succession extending to the Miocene (e.g., Kukla, 1987; Kukla et al., 1988; Sun et al., 1998; An et al., 2001; Sun, 2002). Owing in part to its location at generally lower latitudes (35–40°) than the European loess belts, and in proximity to large deserts, the origin of the silt composing this succession has been attributed to both glacial and desert mechanisms (e.g., Smalley, 1990, 1996; Sun, 2002). Hence, understanding the formation mechanisms of loess materials remains an important research question.

Some studies have attempted laboratory simulations of comminution to assess the roles of various types of physical weathering on silt production. These have included abrasion experiments simulating fluvial (Wright and Smith, 1993), eolian (Kuenen, 1960; Whalley et al., 1982, 1987; Smith et al., 1991; Bullard et al., 2004), and glacial abrasion (Wright, 1995, 1998; Jefferson et al., 1997; Kumar et al., 2006), as well as insolation, salt, and frost weathering (Moss et al., 1981; Pye and Sperling, 1983; Smith et al., 1987; Wright et al., 1998; Wright, 2001). These simulation studies applied a variety of apparatuses to simulate comminution in fluvial, eolian, or glacial settings, or weathering under simulated conditions. The starting materials used in simulated physical weathering studies comprised Brazilian vein quartz which had been freshly crushed to sand size (Whalley et al., 1982, 1987; Wright and Smith, 1993; Wright, 1995, 1998), weakly cemented Neogene sand (Smith et al., 1991), natural dune sand (Pye and Sperling, 1983; Bullard et al., 2004), or other natural sand (Jefferson et al., 1997), and the results varied widely.

Grain size of sediment is influenced to some degree by grain size of the starting material, even for first-cycle sediments. For example, in a study of in situ detritus formed on plutonic, gneissic, and schistose rocks, Blatt (1967) documented that mean size of quartz grains derived from the plutonic and gneissic lithologies exceeded that derived from schists by 1.5–2 times. Blatt (1970) further noted that first-cycle quartz entering the sedimentary cycle exhibits a mean grain size in the coarse sand mode (670 μm), and suggested that fine-grained precursors such as slate and phyllite readily produce quartz silt on weathering. Palomares and Arribas (1993) echoed Blatt's (1967) earlier findings, noting much greater sand production as a result of mechanical weathering from granitoid than schistose starting compositions, owing to the larger crystal sizes and isotropy of granitoids. Similarly, Borrelli et al. (2014) documented that chemical weathering in granitoid and gneissic profiles within the same climatic region resulted in a soil residue characterized by a sand–gravel fraction for the granitoids and by both silt–clay and sand-silt fractions for the gneissic rocks. However, Wright (2002, 2007) suggested that significant amounts of silt can be produced within granitoid weathering profiles, simply by in situ physical comminution.

In light of the history on silt production research, the current study is motivated by two questions: First, in the case of crystalline (igneous or metamorphic) basement, does the foliation present in regionally metamorphosed (gneissic and coarse-grained schistose) rocks strongly affect the rate of silt production? That is, does this starting lithology influence durability, and thus silt production via simulated mechanical weathering? If so, then gneissic and schistose precursors may produce material in the silt fraction more readily than non-foliated (granitoid) precursors, under uniform conditions of simulated physical comminution. Secondly, does climate in which the sand-sized precursor material forms impart a preference in terms of rate of production of silt- or sand-sized material? If so then sand grains from climates characterized by strong chemical weathering, such as the tropics, may disintegrate more readily than sand grains in other climates.

To address these questions, we conducted experiments involving simulated physical weathering of natural sands collected from alluvial/fluvial systems of similar size, but differing in climatic setting. Additionally, although crystalline basement sources underlie all three settings, one system includes contributions from both plutonic and coarse-grained metamorphic (gneissic and schistose) lithologies. Our study differs from other published studies on experimental silt formation in the following ways: 1) the use of natural precursor material collected from alluvial/fluvial systems; 2) the restriction of that starting material to a size that falls within Blatt's (1970) average coarse sand mode thought typical of quartz entering the sedimentary cycle; and 3) use of natural material from sites characterized by very different climatic settings. Results contribute to our understanding of the lithologic and climatic dependence of silt-particle formation via physical weathering.

2. Methods

2.1. Field areas

We selected for sediment sampling alluvial–fluvial systems from three study sites that vary in climatic regime. These sites are: 1) a hot-arid alluvial system in Anza-Borrego Desert, southern California; 2) a hot-humid fluvial system of southeastern Puerto Rico; and 3) a cold-humid proglacial fluvial system in southern Norway (Fig. 1). The alluvial system of Anza Borrego experiences fluvial transport only during rare precipitation events sufficiently intense to generate overland flow. Given sufficient wind velocity, eolian transport might occur during dry conditions, but the position of the study area within a relatively protected "wineglass" valley (Remeika and Lindsay, 1992) mitigates against vigorous eolian processes here, and no sand dunes occur in the area. In southeastern Puerto Rico, the Rio Guyanes drains the tropical uplands and flows perennially with an average discharge of ~2.02 m^3/s (2013 data; USGS National Water Information System). In Norway, rivers in the adjacent Langedalen and Austerdalen valleys drain glaciers emanating from the Austerdalsbreen ice field and join to form the Storelvi River. Flow is perennial and peaks in late summer, with an average discharge comparable to that of the Rio Guyanes. Fig. 2 illustrates the depositional settings of the three field sites.

Only crystalline basement rocks and modern alluvial deposits are exposed in the three sites. However, the bedrock lithology differs among the field sites, with unfoliated tonalite in California, granodiorite with minor metadiorite and metavolcanics in Puerto Rico, and both unfoliated and foliated granitoids in Norway (Fig. 2). Fig. 1 and Table 1 summarize the key climatic and geologic attributes of these study sites, and Fig. 3 displays photomicrographs of the bedrock in each locality. Sediment from the alluvial/fluvial systems was collected from bar surfaces within the alluvial/fluvial transects approximately ~5–7 km from the headwater regions (Fig. 1), to standardize transport distances. Sampling sites were chosen to target the finest-grained part of the bar system (typically the downstream or slackwater portion of lateral bars).