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Micromechanics of quartz sand breakage in a fractal context

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ABSTRACT

From a Quaternary science perspective, sand-sized quartz as well as silt-sized quartz is often acknowledged as final products of glacial abrasion through different evolution mechanisms. This view challenges the existence of any universal comminution process, which may relate the formation of detrital quartz sand and silt. The contribution of grain size, energy input, and crystalline integrity in the scale of quartz crushability has long been the matter of much debate. The present empirical work examines the micromechanics of sand-to-silt size reduction in the quartz material. A series of grinding experiments was performed on Leighton Buzzard Lower Greensand using a high-energy agate disc mill. Analogous conditions to glacial abrasion are provided due to the combined abrasion between grains' asperity tips, and also between grains and rotating smooth tungsten carbide pestle. Simulation of discontinuous grain breakage allowed the examination of grains' crystalline defects. To enable an objective assessment of micromechanics of size reduction, measurements of particle and mode size distribution, fractal indexes and micro-morphological signatures were made. The crushing approach was probed through varied grinding times at a constant energy input, as well as varied energy inputs at constant grinding time. Breakage pathway was inspected via laser diffraction spectroscopy and transmission light microscopy. Results suggested that the grain breakdown is not necessarily an energy-dependent process. Non-crystallographically pure (amorphous) quartz sand and silt are inherently breakable materials through a fractal breakdown process. Results also revealed that the internal defects in quartz are independent from size and energy input.

1. Introduction

Loess, for which quartz silt is the main constituent, is formed through cycles of Quaternary geologic (e.g. crystallization of magma), geomorphic (e.g. solifluction or cryoturbation) and climatic (e.g. thermal or chemical weathering) processes (Smalley et al., 2006b). A good understanding of loess needs silt to receive a descent deal of attention. Silt grains' texture, size, sorting, and crystalline structure have prime control on their interaction with clay, chemicals, and capillary water bonds. Silt's resistance against skeletal forces is also a consequence of grains' surficial and internal properties (i.e. the main supporting units for open spaces within the soil's structure). As such, the purpose of this paper is to make a contribution to that understanding, and to look at the quartz size reduction in the sedimentary, as well as erosion and transport environments (i.e. geomorphic processes), and the controls involved. Silt is formed through size reduction mechanisms. Jefferson et al. (1997) discussed a set of natural geochemical controls in silt formation from quartz-bearing igneous and metamorphic rocks. These controls commenced with an initial transformation of 'high quartz (β-quartz)' into the more densely packed 'low quartz (α-quartz or ordinary quartz)' upon cooling to the hydrothermal temperatures in a granitic system. β-Quartz forms after slow crystallization of siliceous (SiO_2-rich) magma. Sorby (1858) made a detailed study of quartz origin, and implicated the liquid inclusions in quartz to a history of slow crystallization of siliceous magma of granite at low heat (i.e. to a degree below 573 °C) but under great pressure. The quartz product is, in fact, a part of a coarse eutectic of quartz and feldspar (Smalley, 1966). This eutectic reaction, which delivers two new phases from one original phase, leaves its footprints as is shown later herein (see Fig. 4 in Section 4). Further temperature decrease allows the structure of high quartz to distort; such that 6-fold and 3-fold screw axes (60° and 120° inclination) change into 3-fold screw axes (60° inclination). Oxygen–silicon bonds kink and bend, which provides a more densely packed assemblage. The transformation from 'high quartz' to 'low quartz' is displacive (i.e. no bond breakage occurs) but the angle between oxygen bonds change. This causes contraction in the crystal. Contraction induces tensile stresses, normal to the c-axis (about which quartz contracts). These stresses fracture the crystal or induce a defect plane along the c-axis (Smalley, 1966). The defects lead to crushing, delivering 600 μm modal particles into the sedimentary system. There has been much emphasis, within a suite of sedimentological and geochemical works, on identification of the control of such defects on the quartz size reduction upon erosion and transportation. Blatt (1967, 1970) averaged the diameter of quartz from disintegrated crystalline rocks in southern California and Arizona as of 600 to 670 μm (i.e. 720 μm for quartz in Gneisses and massive plutonic rocks and 440 μm for quartz

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in Schist). According to Blatt (1970) this 600 to 700 μm quartz was further crushed by 90%, bringing quartz of a pronounced mode size of 60 μm to the sedimentary environment. The role of quartz internal features in this 90% size reduction was later examined via a suite of abrasion experiments by Krinsley and Smalley (1973) and Moss and Green (1975). Similar abrasion experiments suggested that the 60 μm silt was further crushed into a pronounced modal size of 20 to 60 μm (Kumar et al., 2006) and then to 20 to 30 μm (Jefferson et al., 1997). Such breakdown process suggested the existence of a control, which enables the quartz size reduction under moderate natural stresses (Jefferson et al., 1997).

The mechanism of quartz size reduction has been explained in a fractal framework (Mandelbrot, 1983; Hyslip and Vallejo, 1997). The use of fractal concept allows the simultaneous quantification of fragmentation and grain size distribution (Hyslip and Vallejo, 1997). Fragmentation (i.e. quartz size reduction) is a scale invariant natural process (Smalley et al., 2005), which is conventionally quantified by means of fractal concept (Turcotte, 1986). Fractal is basically a power law relation between number (particle population by mass) and size (particle diameter). Central to the fractal concept is the fractal dimension, which is a measure of the fracture resistance properties of dispersed systems (Brown et al., 1996), such as the crystalline defects in quartz sand and silt. A fractal dimension is a ratio providing a statistical index of complexity comparing how detail in a pattern (strictly speaking, a fractal pattern) changes with the scale at which it is measured. It has also been characterised as a measure of the space-filling capacity of a pattern that tells how a fractal scales differently than the space it is embedded in; a fractal dimension does not have to be an integer.

Lu et al. (2003) used the particle size distribution data to characterise the fractal properties of Leighton Buzzard Sand. They assumed a uniform shape of particles, which is arguable in loess soils (Rogers and Smalley, 1993; Howarth, 2010). They then used the Schuhmann's distribution (Fuerstenau and Han, 2003) accompanied with the Turcotte relation (Turcotte, 1986) (between the fractal dimension and distribution index as discussed in Section 4) and successfully described the fragmentation events. Fractal dimension however should be derived separately for clay and quartz minerals (Wang et al., 2008), due to the different origin of primary and clay minerals (Posadas et al., 2001). This however does not apply to the clean crushed Leighton Buzzard Sand, as this material contains no mineralogical gradient among its size scales.

The present empirical work examines the micromechanics of sand-to-silt size reduction in the quartz material. A series of grinding experiments was performed on Leighton Buzzard Lower Greensand using a high-energy Siebtechnik disc mill. Analogous conditions to glacial abrasion are reportedly provided in disc mills due to the combined abrasion between grains' asperity tips, and also between grains and rotating smooth tungsten carbide pestle. The grinding time and energy input were varied. Breakage pathway was inspected via laser diffraction spectroscopy and transmission light microscopy. Arithmetic fractal measures to describe the breakage process were recorded. These included fractal dimension, relative breakage index, maximum grain size, pronounced modal size and sorting. Results from the grinding experiments together with the microscopy examinations were utilised to derive a timeline for the sand-to-silt size reduction phenomena.

2. Current understanding of silt formation

Silt is a product of events in peridesert, perimountain, and periglacial environments (Smith et al., 2002). Peridesert silt is generated from chemical and salt weathering (Pye, 1995), temperature fluctuations (Smalley et al., 2001) and seasonal wetting/drying and heating/cooling (Smith et al., 2002). Perimountain silt is generated from cold weathering (Zourmpakis et al., 2003) and frost shattering (Wright et al., 1998). Periglacial silt is produced from glacial grinding (Smalley et al., 2005) of granitic (or other rocks such as shale) beds (Sorby, 1858) of glaciers. Less appreciated disintegrating processes include: sub-aerial and fluvial transport actions (Smalley et al., 2006a), loessification (i.e. in-situ dry weathering on carbonate-rich parent material that originally was deposited as alluvium on flood plains during the Pleistocene—see Russell (1944) and Pecsi (1990)) and dry climate weathering (Assallay et al., 1996), desertification (Qiang et al., 2010), and volcanic actions (Pouclet et al., 1999). However, glacial grinding (periglacial) is widely accepted as the main source of present-day silt (Smalley et al., 2006a).

2.1. Geological controls and sand-to-silt size reduction

The significance of internal weakness in quartz was first scientifically described by Moss (1966). In the line of an earlier research work of Wright and Larsen (1909), Moss (1966) classified the quartz into mature (intact) and defected types. Mature quartz has a background of less post-solidification modifications and fracturing–healing cycles, contains more non-undulatory extinction features and is less structurally damaged. This background grants mature quartz a considerable resistance to weathering, high durability and hardness. With non-intact quartz, cracks form along the projected lines of internal defected planes, such as unopened healed fractures.

For non-intact type of quartz, Moss, in 1973, showed the contribution of transient loads in grain breakage. He emphasised that the magnitude of applying static load might not be high enough to trigger the breakage. The transient load of the same magnitude, however, could crush the grain. He differentiated the grain breakage under transient loading environments by using the 'fatigue fracturing' term. This can also be found in an earlier work, in which Moss (1966) showed that controlled-rate cyclic loads of low order can crush the granitic quartz, while static loads of the same value may fail to break a similar grain. He then simulated a fluvial transport system by subjecting the granitic quartz to rotation in a steel drum containing water. Quartz was weakened in the long-term in transient loading environment (i.e. waves and streams), highlighting the fatigue weakening of quartz grains. This agreed with the suggestion of Sharp and Gomez (1986) that grains break through both fatigue and surface fracturing. Fatigue effect was also addressed in Rabinowicz (1976), where certain textural features were linked with splitting events as stresses apply and release. The idea of silt production through fatigue fracturing in fluvial systems however was questioned in the work of Wright and Smith (1993). Small amounts of 2 to 20 μm silts were produced by water–quartz abrasion, whereby significant amounts of 20 to 60 μm silts were generated when rigid ceramic spheres were used in the rotating drum. Wright and Smith (1993) then concluded a higher significance of impact-induced fracturing than fatigue fracturing. In a different attempt, air-abrasion was simulated in Smith et al. (1991) by subjecting 350 to 500 μm-sized Pannonian sand to timed air jet-stream, generating remarkable contents of 20 μm grains in the first hour. Microscopic observations showed strong edge grinding (source of 20 μm fines) and appearance of fresh micro-fractures on large grains during the first hour. A secondary pronounced mode appeared after 16 h at 20 to 40 μm, which then changed into 60 μm. Similar results were reported in Wright et al. (1998). The stepwise size reduction was in a good agreement with the fatigue fracturing concept.

To further examine the controversy within the experimental studies on the effectiveness of aerial/fluvial abrasion in silt production, Jefferson et al. (1997) discussed the significance of quartz internal controls in air-abrasion processes. They compared two similar wind tunnel experiments on two different sand materials (crystallographically perfect quartz in Kuenen (1960) and granitic quartz in Whalley et al. (1982)). Little silt was generated by crushing the crystallographically perfect quartz. The marked effect of quartz internal features can also be traced in the similar abrasion experiments conducted by Wright (1995) and Jefferson et al. (1997), on intact and non-intact quartz sand, respectively. After subjecting 250 to 500 μm freshly crushed Brazilian vein quartz