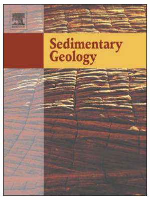
Sedimentary Geology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo



Quantitative analysis of crystal-interface frequencies in granitoids: Implications for modelling of parent-rock texture and its influence on the properties of plutoniclastic sands

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ARTICLE INFO

Article history:
Received 27 June 2017
Received in revised form 22 January 2018
Accepted 23 January 2018
Available online xxxx

Keywords:
Crystal interfaces
Granitoids
Quantitative texture classification
Sediment generation
Compositional data analysis

ABSTRACT

Generation of sediments from crystalline rocks is the result of a complex and incompletely understood suite of processes. The time evolution of the rock-fragment assemblage in sands derived from granitoids is determined by the relative strengths of crystal interfaces and their abundances in the parent rock. In this study we highlight the role of crystal-interface frequencies in granitoids. Strong evidence for non-random texture with significant implications for predicted interface frequencies have been reported in previous studies. We analysed available interface-frequency data from granitoids using methods of compositional data analysis, and connected our results to existing texture classifications. On average, granitoids display a high degree of ordering with significant depletion of isomineralic interfaces relative to expectations based on random texture. Analysis of 210 normalized interface frequency distributions from nine different granitoids reveals a consistent pattern of variation among interface frequencies, which suggests a single underlying petrogenetic process related to the combined effects of nucleation and textural equilibration ("coarsening").

In view of the large scatter of relative interface frequencies within and among granitoids, we propose to model their distribution empirically for the purpose of calibrating sediment-generation studies. Multivariate normal distributions of centred log-ratio transformed relative frequencies are capable of capturing ~95% of the observed variability with a limited number of dimensions. As a rule of thumb, the number of dimensions needed to approximate interface-frequency counts can be taken equal to the number of mineral classes, which is (much) smaller than the number of interface classes. Mathematical analysis shows that the joint variability of rock texture and composition may be factorized into three statistically independent measures: modal composition, crystal-size probability density functions, and normalized interface frequencies. The potential independence of these measures permits objective identification of petrogenetically significant correlations among them, which will be indicated by statistically significant cross-covariances. At this stage, inferences from microscopic texture analysis cannot be extrapolated to the scale of entire drainage basins in which sediments are generated, because insufficient data are available on the large-scale spatial heterogeneity of texture and composition of granitoid parent rocks.

"*Ultimately, it seems evident that, since most geological populations possess interdependent interacting properties, the solutions to problems of geological interest will require multivariate statistical analysis.*" (Griffiths, 1961).

1. Introduction

Generation of sediment from crystalline parent rocks results from a combination of chemical and mechanical weathering. Studies covering the broad field of sediment generation have been mainly focused on the role of chemical weathering in soil formation. The role of mechanical weathering, which is a first-order control on the relation between grain size and petrographic composition of sediments entering the fluvial transport system, has received much less attention and is still poorly understood (Heins, 1993, 1995; Heins and Kairo, 2007; Caracciolo et al., 2012; Weltje, 2012). Petrographic classification schemes of sands are grain-based and include several categories of rock fragments. Rock fragments are defined as grains which are polycrystalline and often also polymineralic. The size-composition evolution of the rock-fragment assemblage of plutoniclastic sands has been analysed in terms of the relative strength of crystal interfaces (Heins, 1992, 1995; Caracciolo et al., 2012). The probability that interfaces are destroyed during mechanical weathering is inversely proportional to their

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https://doi.org/10.1016/j.sedgeo.2018.01.004

strength, which implies that the strongest interfaces will become enriched in the rock-fragment assemblage as a result of progressive breakage. Conversely, the population of monocrystalline grains will become enriched in crystals whose interfaces are weakest on average. The elimination of relatively weak interfaces by breakage implies that rock fragments generated from crystalline parent rocks are expected to display a compositional trend of stronger interfaces with decreasing grain size, owing to the fact that rock fragments generated by breakage will be smaller (and more stable) than the parent rock fragment (Heins, 1995).

Another major control on the time evolution of the rock-fragment assemblage is the relative abundance of the different types of crystal interfaces in the parent rock, which defines the initial conditions for sediment generation (Heins, 1995; Caracciolo et al., 2012). Our approach to modelling of the time evolution of rock-fragment assemblages is based on the fact that these are compositional data, which should be statistically evaluated in the form of log-ratios (Aitchison, 1986). Research has shown that chemical and mechanical weathering trends (Von Eynatten et al., 2003; Von Eynatten, 2004; Weltje, 2012) can be successfully described by linear functions in the centred log-ratio space. Analogously, if mineral interfaces would possess characteristic relative strengths, the evolution of the composition of rock-fragment assemblages shed by different types of granitoid parent rocks should follow parallel trajectories in the centred log-ratio space, and the spread among these trajectories should reflect differences among initial conditions (i.e. parent-rock texture and composition), which define the starting point of each trajectory. Hence, if the effect of variable parent-rock texture and composition can be eliminated from interface data, all trajectories should collapse into a single one, from which relative interface strengths could be reliably estimated.

To accomplish this goal, we need a quantitative model of parent-rock texture, which should at least specify the relations among modal composition and the joint distributions of interface frequencies and crystal size/shape in crystalline rocks (cf. Harvey and Ferguson, 1978) to provide an adequate description of the initial conditions for sediment generation. In this contribution, we provide a statistically compact description of frequency distributions of crystal interfaces in granitoid rocks through re-analysis of legacy data, and we propose guidelines for developing a generic quantitative description of crystalline texture aimed at constraining the initial conditions for sediment generation from granitoid parent rocks, and for testing of petrogenetic hypotheses, based on the formal scheme set out by Griffiths (1961).

2. Size-composition evolution of rock-fragment assemblages

The effects of mechanical weathering on the size-composition evolution of the rock-fragment assemblage may be described in terms of intra- and inter-crystal breakage (Weltje, 2012). Intra-crystal breakage, i.e. fragmentation of individual crystals, is most likely related to the crystallographic properties of minerals. For quartz grains, substantial evidence exists for the presence of microfractures, owing to the presence of dislocations and inclusions, as well as the direct result of the transition from high- to low-quartz during cooling and unloading (Moss, 1966; Smalley, 1966; Blatt, 1967; Moss and Green, 1975; Vollbrecht et al., 1991). Inter-crystal breakage, i.e. fragmentation of rocks along crystal interfaces, is not particularly well understood. The strength of crystal interfaces is inversely proportional to crystal size (Erkan, 1970; Simmons and Richter, 1976), because anisotropy of crystallographic properties creates interface strain owing to unloading, deformation, and temperature variations. In addition, straight crystal interfaces are weaker than more convoluted crystal interfaces which form a tightly interlocked framework.

Interface strengths are expected to differ among isomineralic, non-isomineralic isostructural, and non-isostructural interfaces (Savanick and Johnson, 1974; Heins, 1992, 1995; Caracciolo et al., 2012). The interface analysis of Caracciolo et al. (2012) indicates that in terms of stability, QQ > PP > QP > PK (where Q, P, and K stand for quartz, plagioclase, and K-feldspar, respectively). These are the interfaces with the highest mechanical preservation potential, consistent with the assessment of Heins (1995) regarding the higher preservation potential of non-isomineralic PK and QK interfaces compared to isomineralic KK bonds.

Deduction of interface properties from analysis of natural sediments is fraught with difficulties. In nature, mechanical weathering is enhanced by chemical weathering which acts as an important modifier of interface strength (McWilliams, 1966; Lidstrom, 1968; White, 1976; Pye, 1985, 1986). Moreover, analysis of interface frequencies in rock fragments can only tell us something about inter-crystal breakage. Possible clues to the relative importance of intra-crystal breakage and inter-crystal breakage in sediment generation are contained in discrepancies between the crystal-size distributions (CSDs) of minerals in parent rocks and their size distributions in derived sediments (Aleva, 1956a, 1956b, 1960; Moss, 1966; Smalley, 1966; Blatt, 1967; Hoskin and Sundeen, 1985; Moss and Green, 1975; Van Tassell and Grant, 1980).

3. Models of interface-frequency distributions in crystalline rocks

Quantitative characterization of the texture of granitoids requires information on the spatial distribution of crystals, which may be obtained through analysis of the locations of their centres or through interface counts. This information, which is complementary to the information obtained from analysis of CSDs, may provide valuable clues to petrogenesis (Ehrlich et al., 1972; Jerram et al., 2003). In the field of quantitative texture analysis, the focus lies mostly with analysis of CSDs of minerals (Marsh, 1988; Higgins, 2000, 2006). Evaluation of interface-frequency data for the purpose of quantitative textural analysis of igneous and metamorphic rocks has not been particularly widespread. A measure that is closely related to interface frequency and has been used more often, especially in engineering geology and geomechanics, is the specific surface area or interface density, expressed as interface area per unit volume (Erkan, 1970; Higgins, 2006).

Our choice to characterize texture by means of interface frequencies rather than interface surface area per unit volume is based on the fact that the former are unrelated to the CSD, unlike the latter. Conversion of interface frequencies to interface density (area per unit volume) is straightforward if information on the length of the traverses used during interface counting is available. Interface densities may be calculated according to the following formula (Erkan, 1970; Higgins, 2006):

$$s_i = \frac{2f_i\,d}{a_0} = \frac{2f_i}{L}$$

where i represents an interface between two mineral phases within the rock, s is the interface area per unit volume, f is the number of interfaces, d is the distance between traverses, a_0 is the area of the analysed surface, and L is the total traverse length. The total number of interface classes $k = ½m(m+1)$, where m equals the number of mineral phases in a rock. The total interface density, $S = \sum_{i=1}^{k} s_i$ is often related to mechanical rock properties (Erkan, 1970). An example of the conversion from interface frequencies to densities can be found in Heins (1995).

Caracciolo et al. (2012) provided the first integrated quantitative 2-D description of granitoid rock texture and composition, in which interface frequencies (and lengths), modal composition and CSDs were measured on the same set of samples. The results (summarized in their Fig. 2) show that all three distribution types vary simultaneously. It is intuitively obvious that the modal composition could vary independently from the CSD (at least if the number-frequency

Please cite this article as: Weltje, G.J., et al., Quantitative analysis of crystal-interface frequencies in granitoids: Implications for modelling of parent-rock texture and its influence on the properties..., Sedimentary Geology (2018), https://doi.org/10.1016/j.sedgeo.2018.01.004